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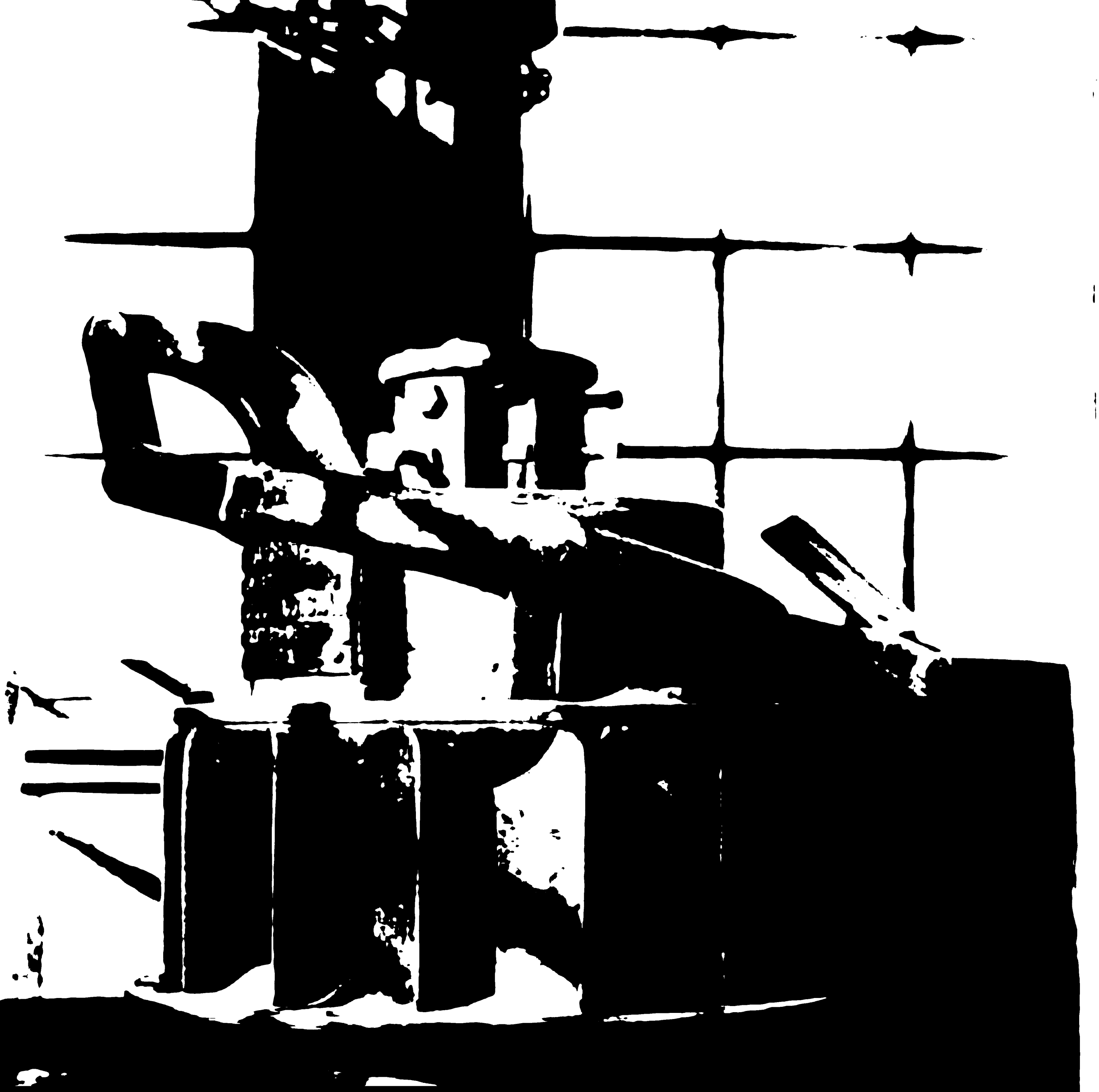

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A STUDY OF THE
EFFECT OF SUBMERGENCE UPON THE
EFFICIENCY OF A WATER TURBINE

A THESIS

SUBMITTED BY

EDGAR DOW GILMAN

FOR

THE DEGREE OF BACHELOR OF SCIENCE

CHEMICAL ENGINEERING COURSE

AND

MAURICE CARL SJOBLOM

FOR

THE DEGREE OF BACHELOR OF SCIENCE

CIVIL ENGINEERING COURSE

University of Wisconsin

1913

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INTRODUCTION

The object of the experiments made in this thesis is to determine the effect on the efficiency of operation of placing a turbine below the level of the tail water; a condition commonly referred to as submergence. Practically all of the questions involving the operation of water turbines in this country have been decided by actual experiment. Theoretical considerations have played but a small part in the development of the American turbine. The purpose of this thesis is to study under practical conditions of operation the effect, if any, of submergence.

The importance of a knowledge of such effect of submergence is self evident. The fact that the condition is but rarely met with in practical installations is one of the causes of the past neglect of the subject; but the vital effect which submergence may have upon those installations where it is unavoidable makes the subject one of prime importance and interest.

The subject comes up in actual practice in several different cases. First: the condition met with in the greatest number of distinct cases is where floods raise the water of the tail race above the level of a turbine which is normally unsubmerged. Second: under conditions of low head wheels of large capacity are used, which must be placed low to prevent the forming of vortices at the entrance. Third:

when several turbines are placed vertically on the same shaft the lower wheel is usually placed quite low in the tail water, in order that the upper wheel may get the entire benefit of the draft tube, and may not be subjected to vortex action.

It has been the unsubstantiated opinion of many hydraulic engineers that turbines should never be placed below the tail water. They have held that this submergence causes a loss of from four to eight percent in the efficiency of the plant, a loss which would sometimes mean the success or failure of a large plant. It has been the supposition of others that at small gate openings submergence might increase the efficiency of the turbine. This idea was based upon the belief that the inflow, under submerged conditions at small gate openings, was changed from the impinging action of unsubmerged condition to a flow similar to that of the reaction type of turbine with its resultant higher efficiency.

A complete and exhaustive investigation of this problem has not as yet been made. Up to 1910 no information whatever was available on the subject. In that year tests were performed for the S. Morgan Smith Turbine Company at the Holyoke Testing Flume. Due to a change in the setting of the wheel in order to obtain submergence, altered conditions of operation may have given rise to results not entirely due to submergence, and the results cannot be taken as conclusive.

Tests along the line of this thesis were carried

out by W. E. Jessup and O. J. Schieber at the Hydraulic Laboratory of the University of Wisconsin in the spring of 1912. No change of setting was used to obtain submerged conditions and the loss in efficiency was determined to be but a trifle over one percent. A continuation of these tests was carried out in the summer of 1912 by C. D. Vaughn, M. F. Rather, and E. C. Noyes; the work in both cases being submitted to The University of Wisconsin as theses for degrees. In the former tests a 12" Victor turbine equipped with a register gate was used, and in the latter tests a 12" Smith-McCormick turbine equipped with a cylindrical gate was used. The conditions of operation were made as nearly identical as possible. In the first test it was found that other conditions being equal the Victor turbine had a slower speed under submergence, while the second test indicated the reverse to be the case. It was found in the latter case that the discharge was greater for a given speed under submerged than under unsubmerged conditions. The effects upon the efficiency of the turbine of the changed condition were so at variance under different gate openings and loads, that the writers could draw no definite conclusions in regard to this phase of the work.

The experimenters in this test have endeavored to continue and supplement the work as begun in the other two tests. The conditions have been made as nearly identical as possible to the former conditions. The 12" Smith-McCormick cylindrical gate turbine was used in these tests.

DESCRIPTION OF APPARATUS

TURBINE

The wheel used in these tests was a 12" inward flow Smith-McCormick turbine, equipped with a cylindrical gate and a draft tube 3.2 ft. long. This turbine was manufactured by the S. Morgan Smith Company of York, Pa.

SETTING

A pit 4 ft. by 5 ft. in plan and 13 ft deep, located in the southwest corner of the Hydraulic Laboratery of The University of Wisconsin, was utilized as a testing pit. A turbine platform, built by Messrs. Jessup and Schieber for use in their tests of 1912, was already in place. This platform was 5.7 ft. above the bottom of the pit. It was made by a double layer of 2" planking at right angles, with two layers of tar paper between the courses. The planking was fastened to 4" by 4" joists which were supported by 4" by 4" posts. This gave a solid base for the wheel and was made water tight by caulking with oakum. The entire platform was then sealed with a 2" layer of 1:1 mortar, leaving the top of the draft tube and the bearing of the turbine exposed. The turbine was then put in its proper position and fastened down solid by means of lag screws. All crevices were then carefully filled with neat cement.

The main openings from the pit below the turbine

platform were three in number; the draft tube admitting the water after it had passed through the turbine, and two circular orifices leading into the weir channel. The discharge through these orifices was regulated by gates. The larger orifice, 16" in diameter, was covered by a sliding wooden gate. The smaller orifice was fitted with a 6" gate valve. For purposes of control rods were extended from these gates up through the turbine platform to the testing platform, built 7.3 ft. above the turbine platform and 13 ft. above the bottom of the pit. No stuffing box was used in passing the rods through the turbine platform but the planks were cut to a close sliding fit, and tar paper carefully fitted around the moving parts. The whole was then covered with neat cement and offered practically no outlet from the pit. A 1" vent pipe extended from the pit to above the level of the testing platform. This allowed free passage of air as the water in the tail rose or fell, thus assuring atmospheric pressure on the surface.

The runner of the turbine was directly connected to a 12" pulley by means of a shaft and a clutch. This pulley was slightly above the testing platform. The shaft was supported by a suitable bearing fastened to an 8" by 8" beam which extended across the testing pit and was embedded in the concrete walls. The testing platform was supported by this same beam. The operation of the turbine gate was accomplished by means of a wooden shaft extending through the testing platform and controlled by a rack and pinion.

A graduated scale was provided for determining the amount of gate opening. The two extremes of the travel of the wooden shaft were marked as full and no gate openings, and the intervening space was divided into eight equal parts.

Plate B shows the various details of the setting.

WATER SUPPLY

Water was supplied by two eight inch centrifugal pumps, pumping from Lake Mendota into a 4 ft. by 4 ft. channel extending along the south side of the laboratory. The combined capacity of the pumps was about eight second feet. The quantity of water supplied was controlled by means of a gate valve on the discharge pipes, and by throttling the engine. For the three-eighths and one-half gate openings one pump was found to be sufficient. For the larger gate openings both pumps were operated together.

In addition to the water supplied by the two pumps a 4" pipe was run from the university pumping system to the 4 ft. by 4 ft. channel. This pipe was provided with a gate valve near the point of discharge. The approximate adjustments of water discharge were made at the pumps, and the final adjustments by means of this 4" pipe.

Iron trash racks were placed around the intake from the lake. These tests were run during the winter months when the lake was frozen up and the difficulty encountered with foreign matter in the previous tests was not met.

METHOD OF MEASURING WATER

After passing through the turbine the water discharged through the orifices in the tail water pit into the 10 ft. channel leading to the measuring weir about 40 ft. away. This weir, 3.0 ft. in length, had end contraction but was not of standard construction, so that Hamilton-Smith's coefficients could not be used. The discharge during this test was obtained from a curve plotted from a calibration made in 1908 by Gage and Wehausen. The calibration was made by the use of a suppressed weir (2.5 ft. in length) located in the laboratory. This was a sharp crested weir with sides of planed lumber extending out beyond the crest, and so constructed as to allow of free passage of air under the nappe. Hamilton-Smith's coefficients could have been used with this weir but even greater accuracy was attained by a volumetric calibration made in 1907. This calibration is described in detail in the bulletin of The University of Wisconsin, No. 216; "Investigation of Flow Through Large Submerged Orifices and Tubes", by Clinton Brown Stewart. By a suitable arrangement of channels the water was made to flow over this standard weir directly into the tail race and over the measuring weir used in this test. Simultaneous readings were taken at the two weirs, and from corresponding heads the calibration curve for the measuring weir was drawn. This is shown on page 22. A table of discharges for every one-thousandths of a foot variation in head on the crest of the weir was taken from this curve drawn to a large scale.

This was done for convenience in computation, and to be sure that no error in discharge would result from a mistake in reading the curve. This table is given on pages23 and 24 .

The head on the crest was measured by a hook gage in a still basin connected to the channel eight feet back from the weir. By means of a vernier differences in head to one one-thousandth of a foot could be read. The zero reading of the scale was determined by a surveyor's level.

The gages used in measuring the elevations of the head and tail water were placed on the wall near the 3 ft. weir, so that one man could read all gages. They consisted of ½" glass tubing fastened to scale boards graduated to .01 ft. The tail water gage was connected by a ½" pipe to a perforated pipe 1½" in diameter and about 3 ft. long, placed in a horizontal position in the tail water chamber at an elevation below that of the lowest tail water used. The head water gage was connected by a ½" pipe to a horizontal pipe open at both ends in the head water chamber. The ½" piping from the gages was placed in the weir channel, and passed into the tail water chamber through the 16" orifice. The head water gage pipe then passed upward and through the turbine platform. These two pipes passing through the 16" orifice at the bottom prevented the complete closure of the tail water chamber. However, the discharge through the opening that was left was below the minimum discharge required and did not interfere with the regulation of heads.

The gage scales for both gages were set at the same

zero, so that the difference between the head and tail water elevations as read would always give the effective head directly under which the turbine was operating.

CONTROL OF HEADS AND SUBMERGENCE

The purpose of a setting such as has been previously described, was to provide a means of varying the elevation of the tail water at will without changing the setting of the turbine. The tail water head was controlled by varying the area of discharge through the 16" and the 6" openings from the wheel pit below the turbine platform. The wooden gate covering the 16" orifice served as a rough means of adjustment; final adjustment being obtained by means of the gate valve from the 6" orifice.

DETERMINATION OF HEAD

The depth of pit and elevation of discharge weir in the location selected for making these tests limited the allowable effective head and depth of submergence. In order to obtain a suitable degree of submergence and use the same head as used in the unsubmerged condition, the effective head had to be limited to 5½ ft. This gave a range of nearly 2½ ft. in the elevation of the tail water between the two conditions.

BASIS OF SUBMERGENCE

In running these tests the actual conditions of

operation used in the previous tests were approximated as closely as possible. The same degree of submergence was used, i.e., when running under the submerged conditions the tail water was brought to the same height as was used in the previous tests. The datum plane for submergence as stated in the previous tests was taken as the level of the turbine platform. It has been thought advisable to change this datum plane. Such a plane seemed illogical in that the plane might vary with the setting of different turbines and has no relation to the flow of water into the turbine. For the purposes of these tests it did not make any difference where the datum plane was chosen, but it was thought that the decision should be clearly stated so that when future and more comprehensive studies of the subject are made the submergence as expressed in this test may be compared with that of other tests. For this reason a datum plane dependent upon the flow of water into the turbine and not upon the setting was chosen. There were three planes considered. (See plate B .) Plane A at the beginning of submergence when the water just reaches the blades; plane "B", the level at which water first begins to discharge into the draft tube; and plane "C", the level at which the runner is completely submerged. The last named plane seems the most desirable from all points of view, as it depends neither upon the setting nor upon the shape of the blades. It appears to affer the best possibilities for comparison with other tests on other makes and types of turbimes, and was chosen as a datum plane from which to express

the depth of submergence.

As it was desirable to keep the submergence the same as in the previous tests the difference in level between the bottom of the turbine platform and plane "C", as found, was subtracted from 1½ ft. (the submergence expressed in the previous tests) and the result used as the submergence in these tests with the new datum plane. This gave a submergence of 0.5 ft. It must be borne in mind that actually the conditions were identical to those of the preceding tests.

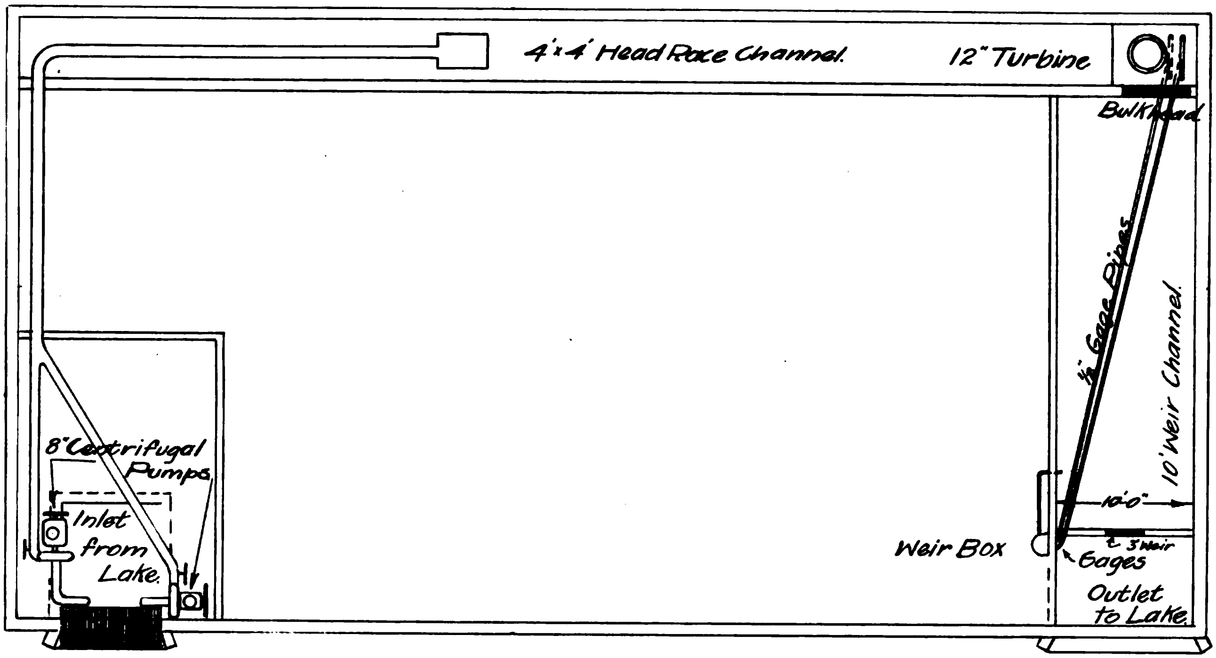
MEASUREMENT OF POWER

The load carried by the turbine was measured by the usual prony brake method. The brake was placed upon the 12" pulley before mentioned. A two foot arm communicated the load through a triangular wooden bell crank to a small platform scale. A small continuous counter was used to measure the speed of the wheel. The counter was operated by a spring and cord attached to a pin set eccentrically in the top of the shaft of the turbine. Plate F shows the arrangement.

GENERAL

Due to the noise in the laboratory a speaking tube was provided for communication between the observer at the gages and the observer at the wheel. See plate I .

Plate A



Plan of Hydraulic Laboratory.
Showing Arrangement of Apparatus.

Plate B

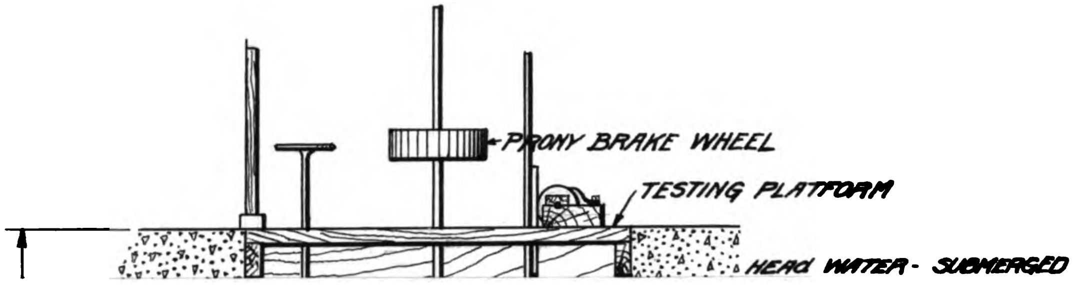
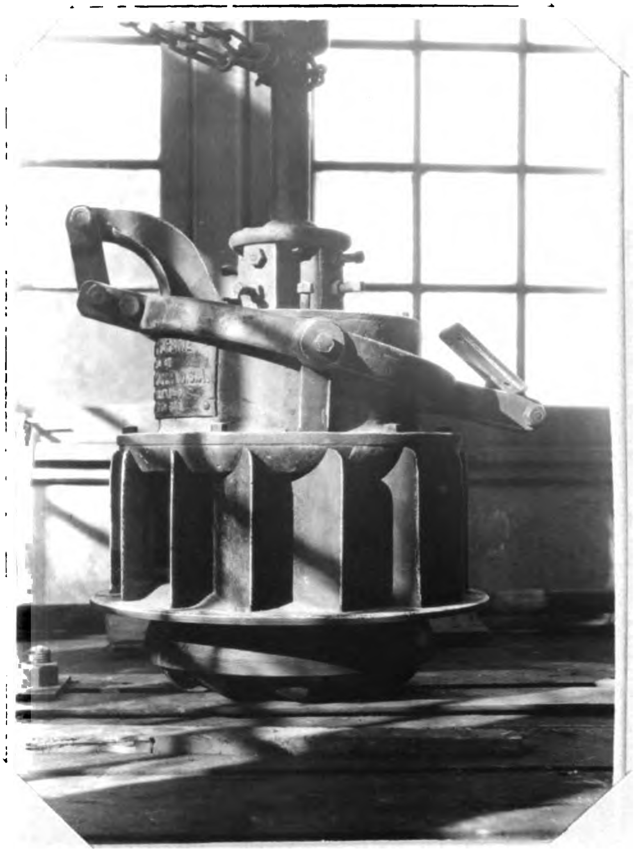


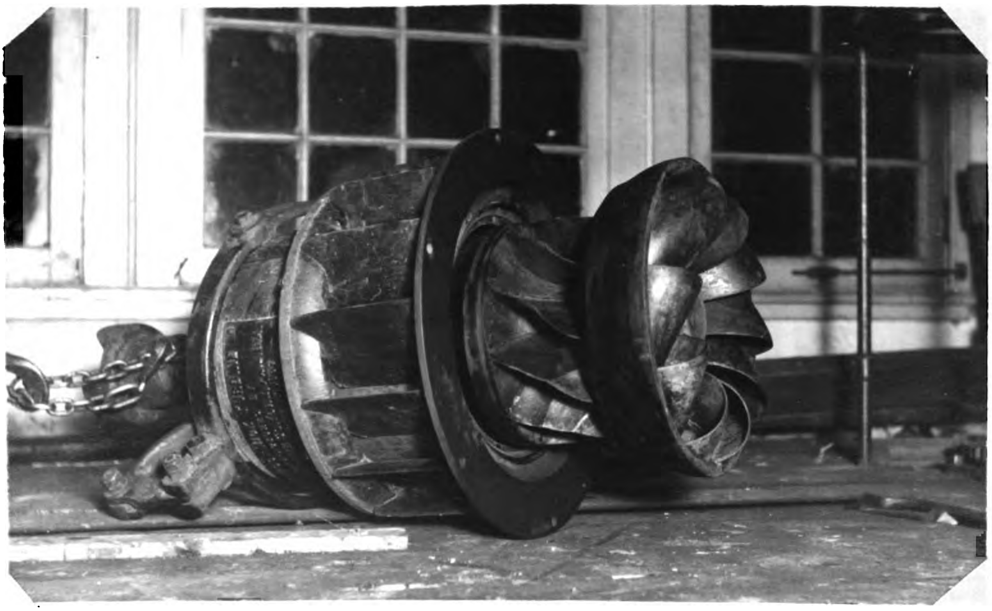
Plate B



12" SMITH - McCORMICK TURBINE

CYLINDER GATE

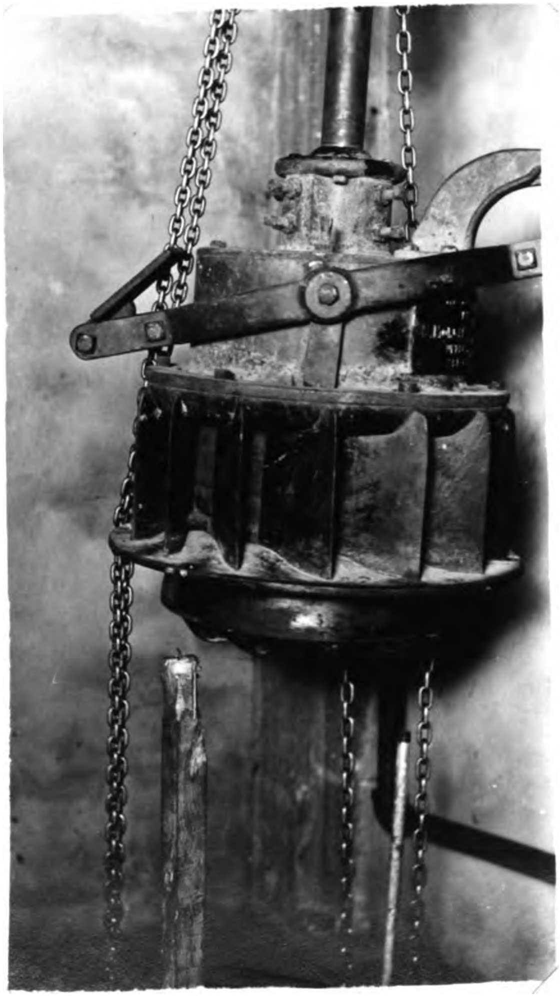
Plate D



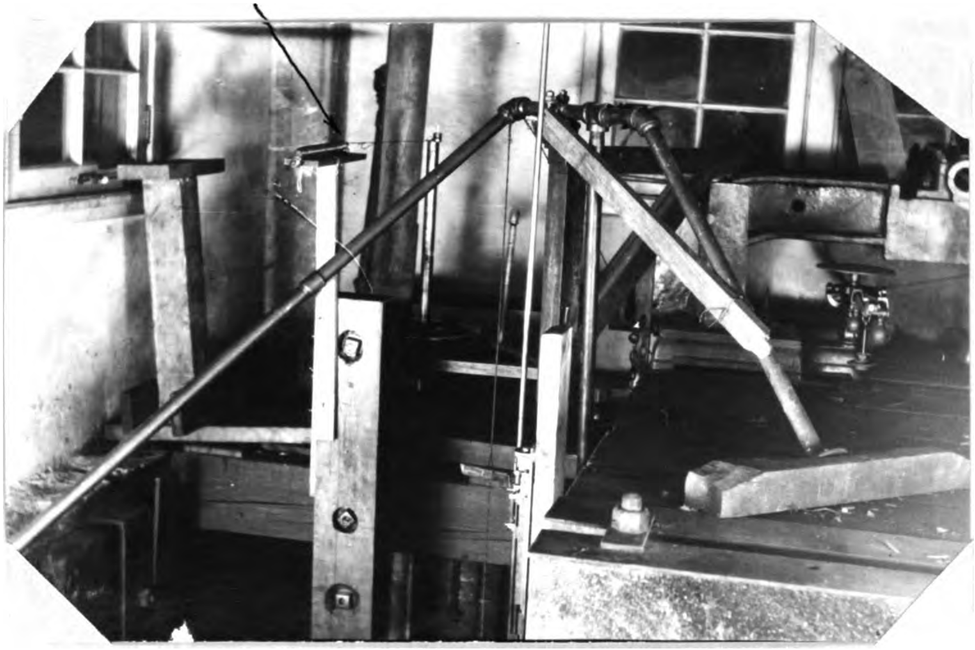
12" SMITH McCORMICK TURBINE

RUNNER PARTLY REMOVED

Plate E

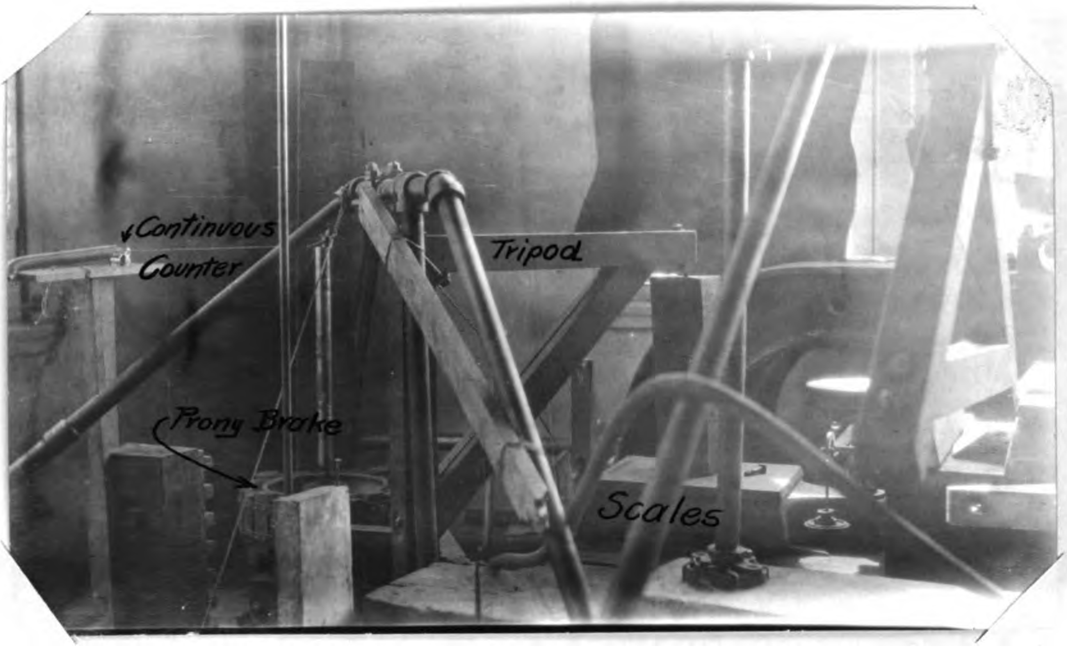


12" SMITH-McCORMICK TURBINE

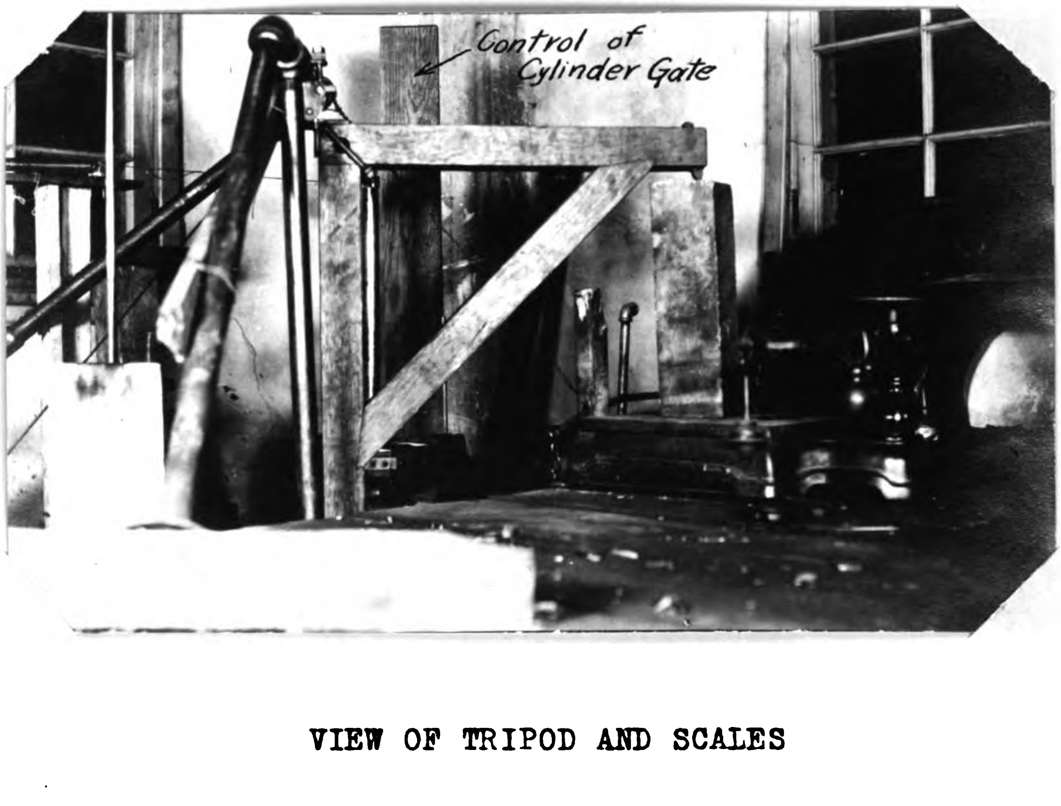


Continuous Counter

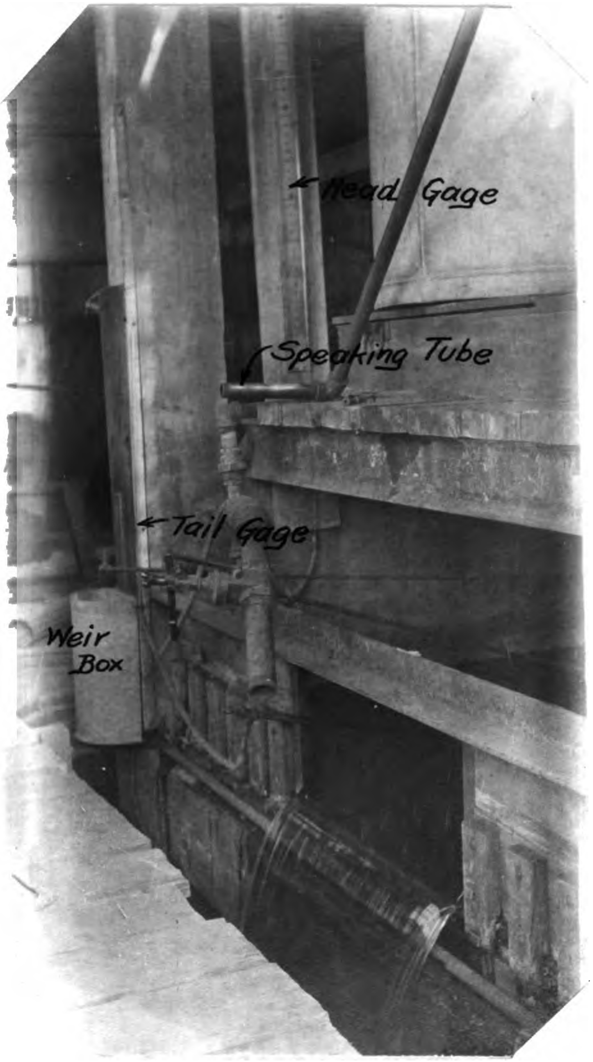
VIEW OF TESTING PLATFORM



VIEW OF TESTING PLATFORM



VIEW OF TRIPOD AND SCALES



VIEW OF 3 Ft. WEIR, WEIR BOX, GAGES, and SPEAKING TUBE

METHOD OF CONDUCTING TESTS

Tests Made

Tests were run at 3/8, 1/2, 5/8, 3/4, 7/8, and 8/8, under the unsubmerged and the one-half foot submerged conditions. At each gate opening of each condition a series of tests with varying loads was made, ranging from the maximum load that the turbine would carry and move freely to the runaway speed. In order to successfully plot the curves of these tests it was found necessary to make from eight to ten tests for each setting of the turbine. Therefore, the data of these experiments represent tests at six different gate openings with the turbine unsubmerged, and at the same six gate openings with the turbine submerged, and is primarily embodied in 105 tests. In addition 15 tests were run over to show how closely the work could be made to check, giving a total of 120 tests made to arrive at the conclusions of this thesis. The tests that were run over were such as to give the curves at the maximum efficiency for the 3/4 gate submerged and unsubmerged and the 7/8 gate submerged conditions. The results of these tests are plotted on the same sheets with the original data and show how closely the work could be made to check, and indicate the extent of the experimental error under the conditions surrounding the operation of the turbine.

Cautions

The purpose of these tests was to discover the effect of submergence upon the efficiency of the turbine. In order that any effect upon the results obtained could b be attributed to submergence alone, every detail of conducting the test at a given gate opening was maintained as nearly constant as possible for the two runs, one at the submerged and the other at the unsubmerged condition. The gate was set at the desired opening and tests of both conditions were made before moving the gate to the next opening. In order that the personal equation of the observers would affect both runs alike the same apparatus was handled by one observer throughout the tests.

Outline of Test

In starting a test at a given gate opening the gate was set at the desired opening and the centrifugal supply pumps started. These were then regulated as near as possible to give the amount of water necessary to operate the wheel under the 5½ ft. head used. The final adjustment of water supply and head was made with the 4" valve from the university pumping system. Continual regulation throughout the run was necessary as the load on the wheel was changed; for a greater quantity of water was required for the the greater loads and slower speeds then for the lighter loads and faster speeds.

The submerged run was sometimes taken first and sometimes the unsubmerged, whichever was the most convenient at the time of starting. It was usually found most convenient to start the run under full load conditions so that a suitable number of tests could be determined upon between full load and no load.

When the water levels had been adjusted to the desired points the observations were started. Two persons were required to take readings and to keep the loads and heads constant. Observer No.1 was located on the platform above the wheel pit on a level with the prony brake. He acted as recorder, maintained the brake load constant, and recorded the readings of the continuous revolution counter. Observer No. 2 was located at the weir. He read the height of the water over the crest of the weir and the elevations of the head and tail race water. These readings he recorded on a paper which was given to observer No.1 to copy on the data sheets. Observer No.2 also took charge of the regulation of the water supply which had to be changed between each test.

Readings of the hook gage and the head and tail gages were taken at two minute intervals over a period of six minutes making 4 readings for each load. When observer No.2 had the water regulated and was ready to start he informed observer No.1 of this fact by means of the speaking tube. Observer No.1 then checked his load and

held it balanced. At one sharp rap observer No.2 began to take his readings. He was provided with a watch and kept his own time. It made no difference in his readings if the time were over or under several seconds. Observer N0.1 was provided with a stop watch. As soon as possible after the rap indicating the start of the test he to took a reading of the continuous counter, at the same time starting the stop watch. At the end of about 5½ minutes he took another reading, and stopped the stop watch. These readings of the continuous counter were the only readings in which the time element played an exacting part.

When a satisfactory set of readings was obtained the brake was adjusted for the next load and the proper regulation of water supply made. Several minutes were allowed for conditions to become settled before taking readings for the new set of conditions.

Following this page is a reproduction of the data sheets used in recording data for the test at one-half gate. This form for recording and computing the data was used for all the tests. The complete data were too bulky to include in this thesis but may be found on file at the Hydraulic Laboratory of The University of Wisconsin.

DATA SHEET **COLLEGE OF ENGINEERING, UNIVERSITY OF WISCONSIN**

Experiment on 12" Smith-McCormick Turbine

Data by Gilman- Sjoblom Computed by Gilman-Sjoblom

Date February 5, 1913 Checked by Sjoblom-Gilman

General Data

1/2 Gate - Unsubmerged

DATA SHEET COLLEGE OF ENGINEERING, UNIVERSITY OF WISCONSIN

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Data by Gilman-Sjoblom **Computed by** Gilman-Sjoblom

Date February 5, 1913 **Checked by** Sjoblom-Gilman

General Data

1/2 Gate - Submerged

Explanation of Data Sheets

Column 1 shows the time as recorded by the stop watch in taking the readings of the continuous revolution counter shown in column 7.

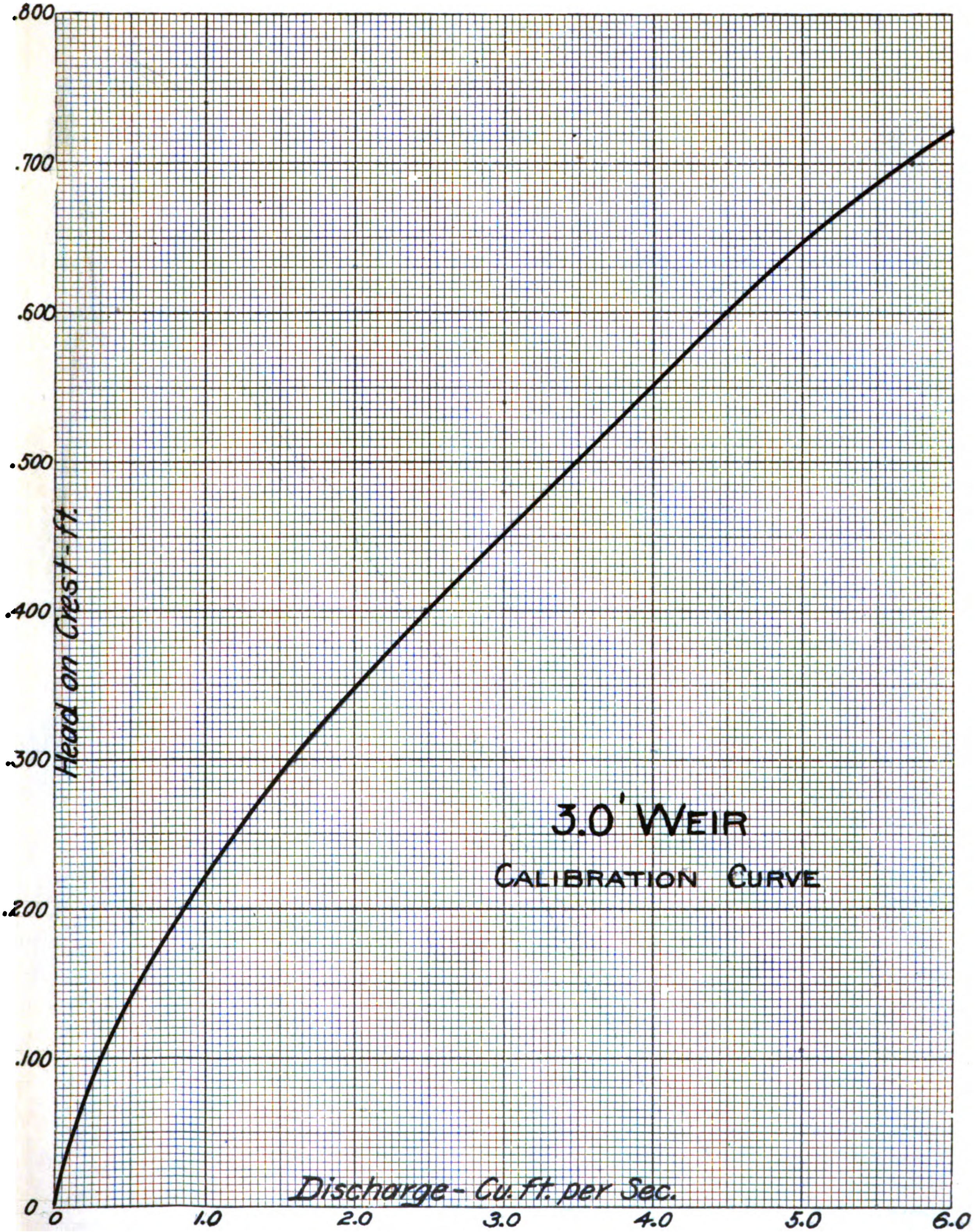
Columns 2 and 3 are the heights of the head and tail water respectively. As previously stated these two gages were set with their zero readings at the same level. Hence the difference between the readings will be the effective head acting upon the turbine. This is shown in column No. 4.

Column 5 shows the reading of the hook gage at the weir, and column 6 shows the discharge corresponding to the average readings of the hook gage for the test. This discharge was obtained from the calibration table on pages 23 and 24.

Column 7 shows first the reading of the continuous revolution counter at the time of starting the stop watch and second the reading at the time of stopping the watch. The difference records the number of revolutions of the wheel during the time recorded in column 1. In column 8 this is reduced to R.P.M.

The net brake load is shown in column 9. Before starting each test the scales were checked at no load except the weight of the tripod arm and were made to balance by adding small weights to the platform of to the lever. The scales had been previously calibrated and no appreciable error was found. Any error would not affect the purposes of this thesis, however.

In columns 10, 11, 12, 13, 14, are shown the brake horsepower, the theoretical horsepower, the efficiency, the velocity of the periphery of the wheel (V'), and the ratio (ϕ) of this velocity to the theoretical velocity of the jet, ($\sqrt{2gh}$), respectively. These are the results of computation and the methods of obtaining these results is discussed under the next section.


3.0' Weir
Calibration Curve
Head on Crest - ft.
Discharge - Cu. ft. per Sec.
.800
.700
.600
.500
.400
.300
.200
.100
0
0
1.0
2.0
3.0
4.0
5.0
6.0

WEIR DISCHARGE TABLE

FOR 3 ft. WEIR

H - Head in feet

Q - Discharge in cubic feet per second

H	Q	H	Q	H	Q	H	Q	H	Q
.400	2.470	.438	2.822	.476	3.216	.514	3.634	.552	4.034
.401	2.479	.439	2.831	.477	3.227	.515	3.645	.553	4.046
.402	2.488	.440	2.840	.478	3.238	.516	3.656	.554	4.058
.403	2.497	.441	2.850	.479	3.249	.517	3.667	.555	4.070
.404	2.506	.442	2.860	.480	3.260	.518	3.678	.556	4.082
.405	2.515	.443	2.870	.481	3.271	.519	3.689	.557	4.094
.406	2.524	.444	2.880	.482	3.282	.520	3.700	.558	4.106
.407	2.533	.445	2.890	.483	3.293	.521	3.710	.559	4.118
.408	2.542	.446	2.900	.484	3.304	.522	3.720	.560	4.130
.409	2.551	.447	2.910	.485	3.315	.523	3.730	.561	4.141
.410	2.560	.448	2.920	.486	3.326	.524	3.740	.562	4.152
.411	2.569	.449	2.930	.487	3.337	.525	3.750	.563	4.163
.412	2.578	.450	2.940	.488	3.348	.526	3.760	.564	4.174
.413	2.587	.451	2.950	.489	3.359	.527	3.770	.565	4.185
.414	2.596	.452	2.960	.490	3.370	.528	3.780	.566	4.196
.415	2.605	.453	2.970	.491	3.381	.529	3.790	.567	4.207
.416	2.614	.454	2.980	.492	3.392	.530	3.800	.568	4.218
.417	2.623	.455	2.990	.493	3.403	.531	3.810	.569	4.229
.418	2.632	.456	3.000	.494	3.414	.532	3.820	.570	4.240
.419	2.641	.457	3.010	.495	3.425	.533	3.830	.571	4.252
.420	2.650	.458	3.020	.496	3.436	.534	3.840	.572	4.264
.421	2.660	.459	3.030	.497	3.447	.535	3.850	.573	4.276
.422	2.670	.460	3.040	.498	3.458	.536	3.860	.574	4.288
.423	2.680	.461	3.051	.499	3.469	.537	3.870	.575	4.300
.424	2.690	.462	3.062	.500	3.480	.538	3.880	.576	4.312
.425	2.700	.463	3.073	.501	3.491	.539	3.890	.577	4.324
.426	2.710	.464	3.084	.502	3.502	.540	3.900	.578	4.336
.427	2.720	.465	3.095	.503	3.513	.541	3.911	.579	4.348
.428	2.730	.466	3.106	.504	3.524	.542	3.922	.580	4.360
.429	2.740	.467	3.117	.505	3.535	.543	3.933	.581	4.371
.430	2.750	.468	3.128	.506	3.546	.544	3.944	.582	4.382
.431	2.759	.469	3.139	.507	3.557	.545	3.955	.583	4.393
.432	2.768	.470	3.150	.508	3.568	.546	3.966	.584	4.404
.433	2.777	.471	3.161	.509	3.579	.547	3.977	.585	4.415
.434	2.786	.472	3.172	.510	3.590	.548	3.988	.586	4.426
.435	2.795	.473	3.183	.511	3.601	.549	3.999	.587	4.437
.436	2.804	.474	3.194	.512	3.612	.550	4.010	.588	4.448
.437	2.813	.475	3.205	.513	3.623	.551	4.022	.589	4.459

.590	4.470	.626	4.866	.662	5.230	.698	5.716	.734	6.162
.591	4.481	.627	4.877	.663	5.237	.699	5.728	.735	6.175
.592	4.492	.628	4.888	.664	5.245	.700	5.740	.736	6.188
.593	4.503	.629	4.899	.665	5.252	.701	5.752	.737	6.201
.594	4.514	.630	4.910	.666	5.260	.702	5.764	.738	6.214
.595	4.525	.631	4.922	.667	5.290	.703	5.776	.739	6.227
.596	4.536	.632	4.934	.668	5.320	.704	5.788	.740	6.240
.597	4.547	.633	4.946	.669	5.350	.705	5.800	.741	6.253
.598	4.558	.634	4.958	.670	5.380	.706	5.812	.742	6.266
.599	4.569	.635	4.970	.671	5.392	.707	5.824	.743	6.279
.600	4.580	.636	4.982	.672	5.404	.708	5.836	.744	6.292
.601	4.591	.637	4.994	.673	5.416	.709	5.848	.745	6.305
.602	4.602	.638	5.006	.674	5.428	.710	5.860	.746	6.318
.603	4.613	.639	5.018	.675	5.440	.711	5.872	.747	6.331
.604	4.624	.640	5.030	.676	5.452	.712	5.884	.748	6.344
.605	4.635	.641	5.041	.677	5.464	.713	5.896	.749	6.357
.606	4.646	.642	5.052	.678	5.476	.714	5.908	.750	6.370
.607	4.657	.643	5.063	.679	5.488	.715	5.920	.751	6.383
.608	4.668	.644	5.074	.680	5.500	.716	5.932	.752	6.396
.609	4.679	.645	5.085	.681	5.512	.717	5.944	.753	6.409
.610	4.690	.646	5.096	.682	5.524	.718	5.956	.754	6.422
.611	4.701	.647	5.107	.683	5.536	.719	5.968	.755	6.435
.612	4.712	.648	5.118	.684	5.548	.720	5.980	.756	6.448
.613	4.723	.649	5.129	.685	5.560	.721	5.993	.757	6.461
.614	4.734	.650	5.140	.686	5.572	.722	6.006	.758	6.474
.615	4.745	.651	5.147	.687	5.584	.723	6.019	.759	6.487
.616	4.756	.652	5.155	.688	5.596	.724	6.032	.760	6.500
.617	4.767	.653	5.162	.689	5.608	.725	6.045	.761	6.513
.618	4.778	.654	5.170	.690	5.620	.726	6.058	.762	6.526
.619	4.789	.655	5.177	.691	5.632	.727	6.071	.763	6.539
.620	4.800	.656	5.185	.692	5.644	.728	6.084	.764	6.552
.621	4.811	.657	5.192	.693	5.656	.729	6.097	.765	6.565
.622	4.822	.658	5.200	.694	5.668	.730	6.110	.766	6.578
.623	4.833	.659	5.207	.695	5.680	.731	6.123	.767	6.591
.624	4.844	.660	5.215	.696	5.692	.732	6.136	.768	6.604
.625	4.855	.661	5.222	.697	5.704	.733	6.149	.769	6.617
								.770	6.630

METHOD OF COMPUTATION

At the end of each test the readings of the gages were averaged, and these average results from which the computations were made are included in this thesis. The original data sheets were explained in the previous section. The tabulated data as included here contain the averages of the four observations on the apparatus. The column heads are self-explanatory.

Brake Horsepower

The usual formula for brake horsepower is

$$B.H.P. = \frac{2\pi rnw}{33000}$$

where: r - length of brake arm in feet (2.0)
n - revolutions per minute
w - net brake load in lbs.

This is reduced to a simpler form by substituting the known factors, as follows:

$$B.H.P. = \frac{2 \times 3.1416 \times 2}{33000} \times n \times w = .00381nw.$$

Theoretical Horsepower

The theoretical power available in the water is equal to the weight of the water supplied, multiplied by the distance through which it falls. This, in horsepower may be expressed as follows:

$$T.H.P. = \frac{Q \times 62.5 \times h}{550} = \frac{Qh}{8.8}.$$

Efficiency

Efficiency is the ratio of the work taken from a machine to the work put into it. In this case it is the ratio of the brake horsepower to the theoretical horsepower. This ratio is reduced to percent by multiplying by 100.

V'

V' represents the velocity of the periphery of the wheel in feet persecond. For this wheel, 12" in diameter, it is represented by the following equation:

$$V' = \frac{\pi \times 1 \times n}{60} = .05236 \times n$$

ϕ (PHI)

This is the ratio of the peripheral velocity of the turbine runner to the theoretical velocity ($\sqrt{2gh}$) of a jet of water discharging under the head used. It is represented by the following equation:

$$\phi = \frac{V'}{\sqrt{2gh}} = \frac{V'}{8.03\sqrt{h}}$$

Q_1

The discharge curves are plotted under equivalent one foot heads. This discharge is found by the following equation:

$$Q_1 = \frac{Q}{\sqrt{h}}$$

EXPLANATION OF CURVES

The best manner in which to show the effect which submergence has upon the operation of the wheel is to show the results graphically. Conditions of operation were plotted which would show most readily any effect which might exist.

For each gate opening the following curves were plotted on separate sheets:

1. Curves showing the relation of brake load in pounds to revolutions per minute for both the unsubmerged and submerged conditions.

2. Curves showing the relation of the efficiency of operation in percent to ϕ, the ratio of the peripheral velocity to $\sqrt{2gh}$, for both conditions.

The two curves cited above are the most important for the purposes of these tests. The curve sheets follow immediately after the data from which they were plotted so that comparison will be simplified.

In addition the following curves were plotted as adding information to the operation of the turbine:

3. Curves showing the maximum efficiency with the different gate openings for both conditions.

4. Curves showing the relation between the discharge in cubic feet per second and ϕ.

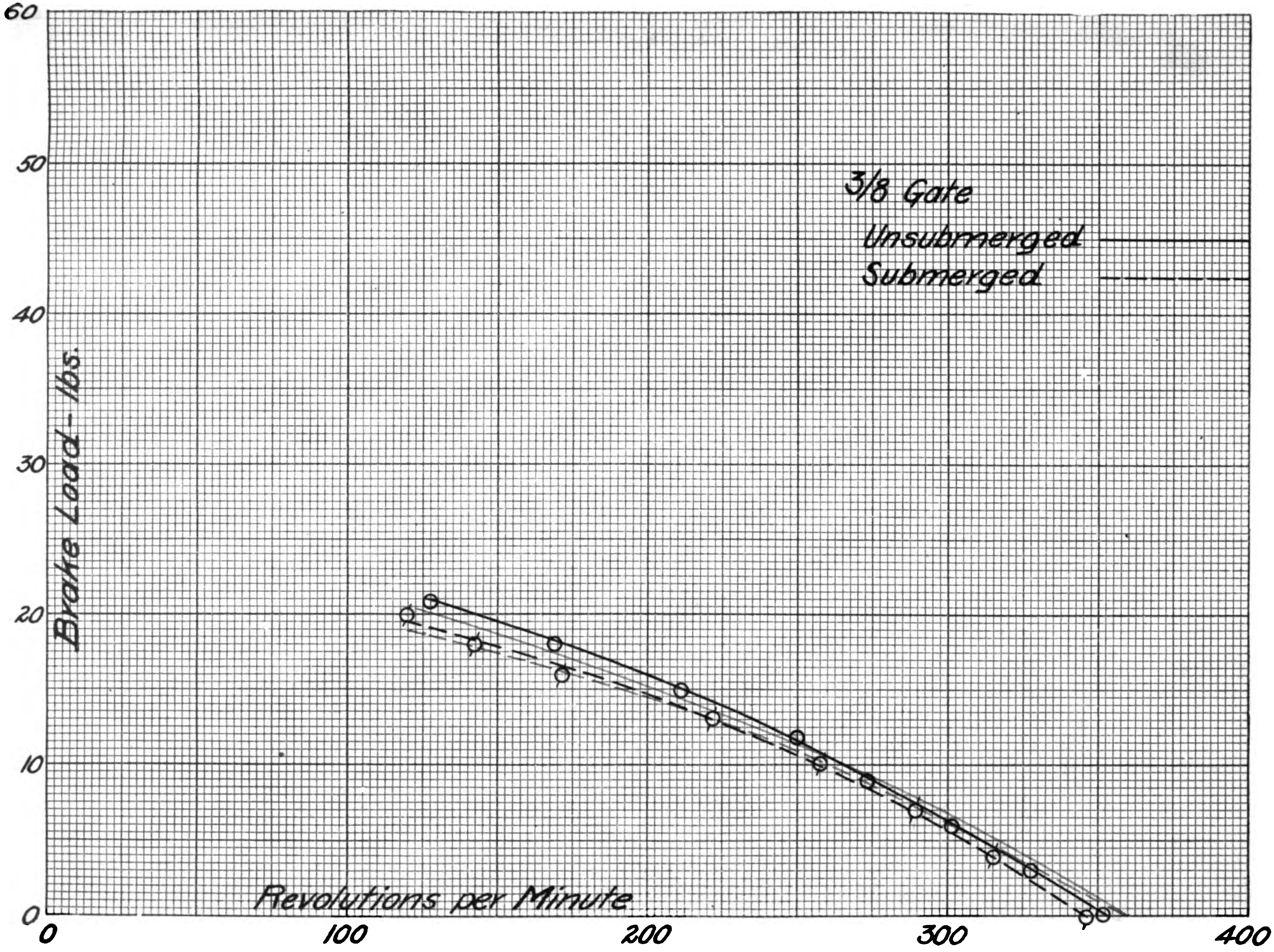
5. Curves showing the relation between the input and the output. (T.H.P. : B.H.P.)

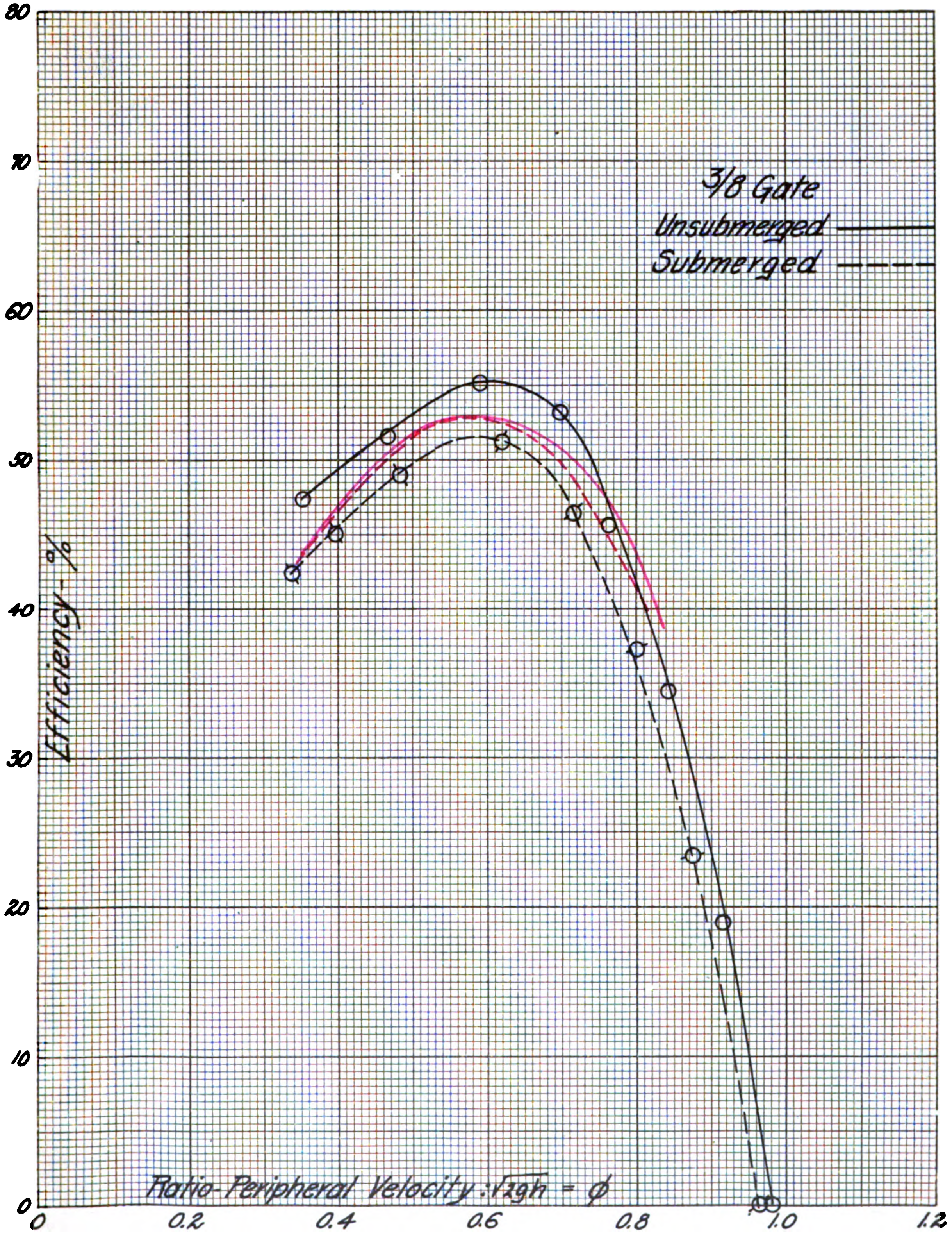
Additional tests were made at the 7/8 submerged and the 3/4 submerged and unsubmerged. The data thus obtained were plotted together with the original data, and are shown by a fine black line. This was done with the idea of determining how closely the tests could be made to check and how

great the experimental error surrounding these tests was. The result seems to indicate that the experimental error is greater than any difference due to the effect of submergence. The causes of this will be discussed later.

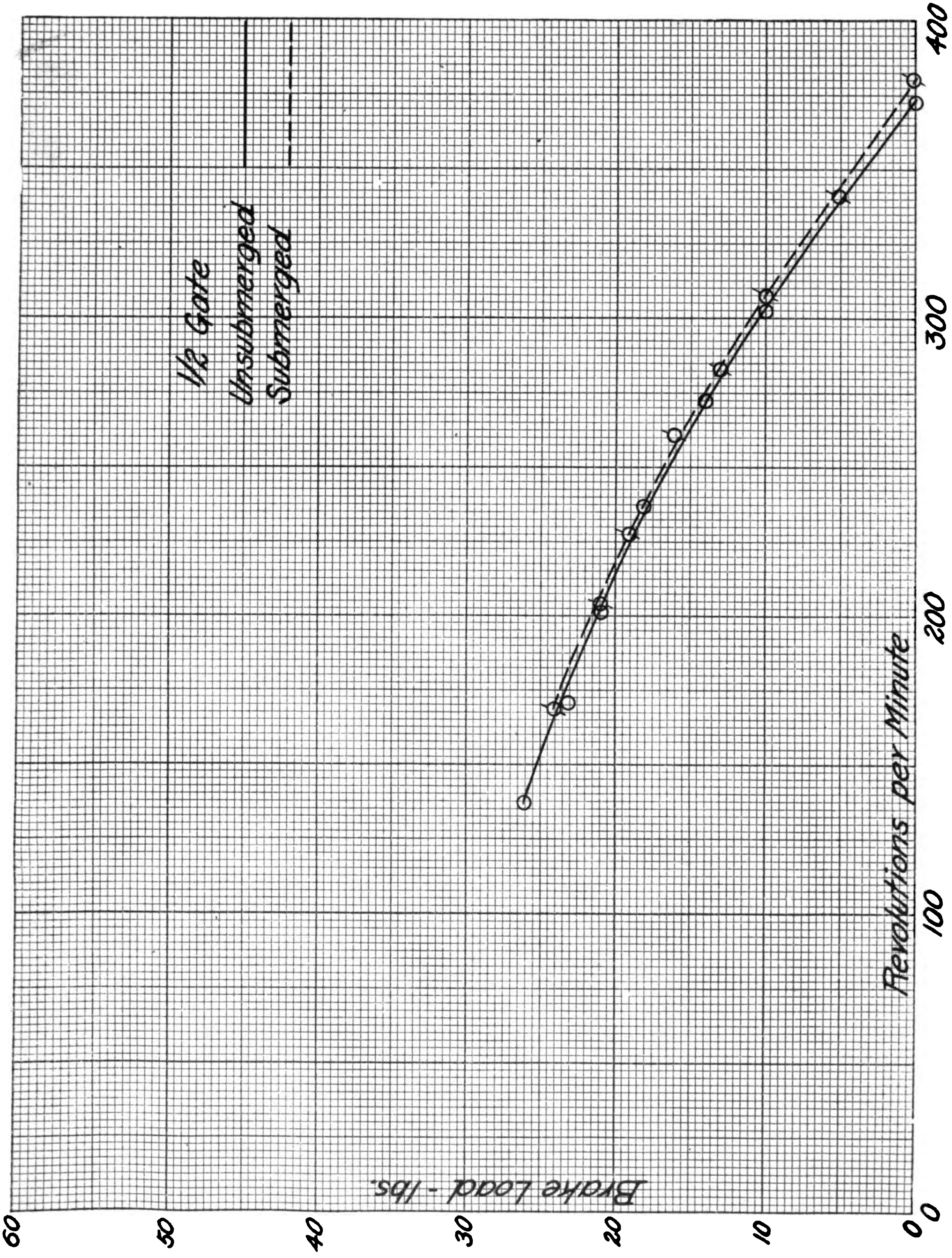
In addition to all the curves cited above, which were plotted from data taken in these tests, there have been plotted upon the same sheets the data as determined by Messrs. Rather, Vaughn, and Noyes in their experiments of 1912. Their experiments were made upon the same turbine and in as nearly an identical manner to those of this series of tests as it was possible to make them. The results as shown graphically by the red lines on the curve sheets show considerable variation from the results as determined by these experiments. The various causes for this will be discussed in a later section.

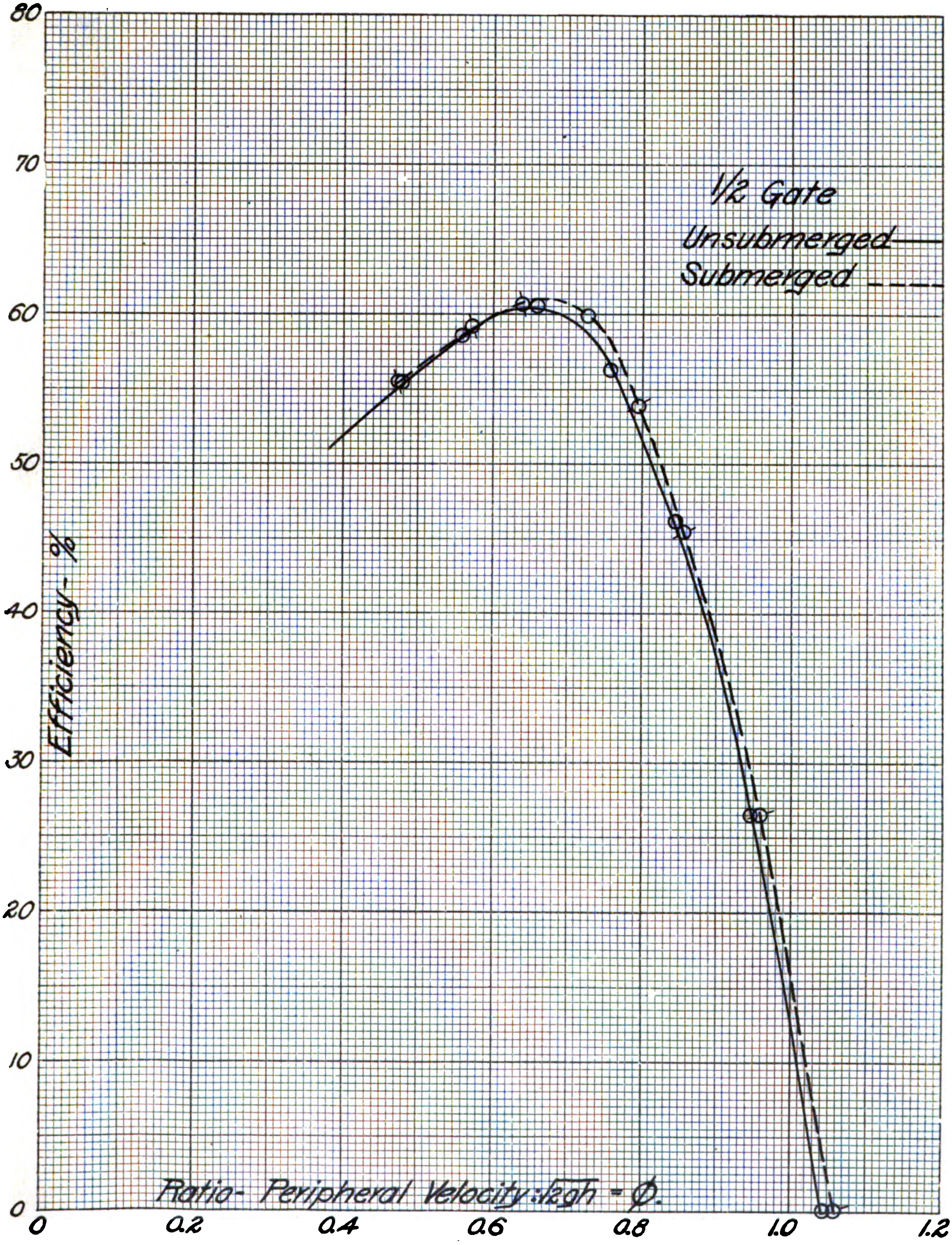
3/8 GATE - 5½ ft. HEAD


3/8 Gate
Unsubmerged
Submerged
Brake Load - lbs.
Revolutions per Minute
0
10
20
30
40
50
60
0
100
200
300
400

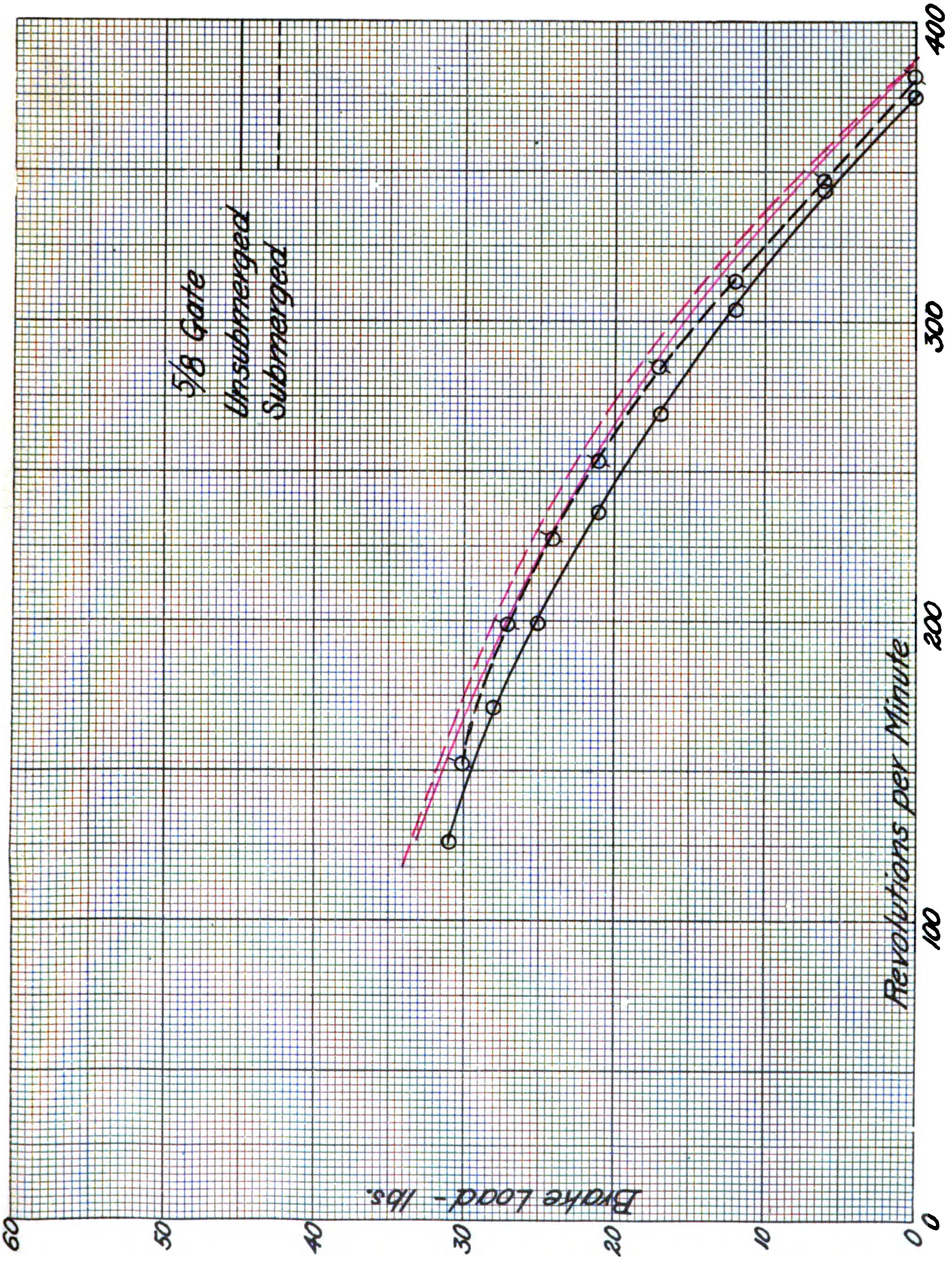

3/8 Gate
Unsubmerged
Submerged
Efficiency - %
Ratio - Peripheral Velocity : $\sqrt{2gh} = \phi$
0
10
20
30
40
50
60
70
80
0
0.2
0.4
0.6
0.8
1.0
1.2

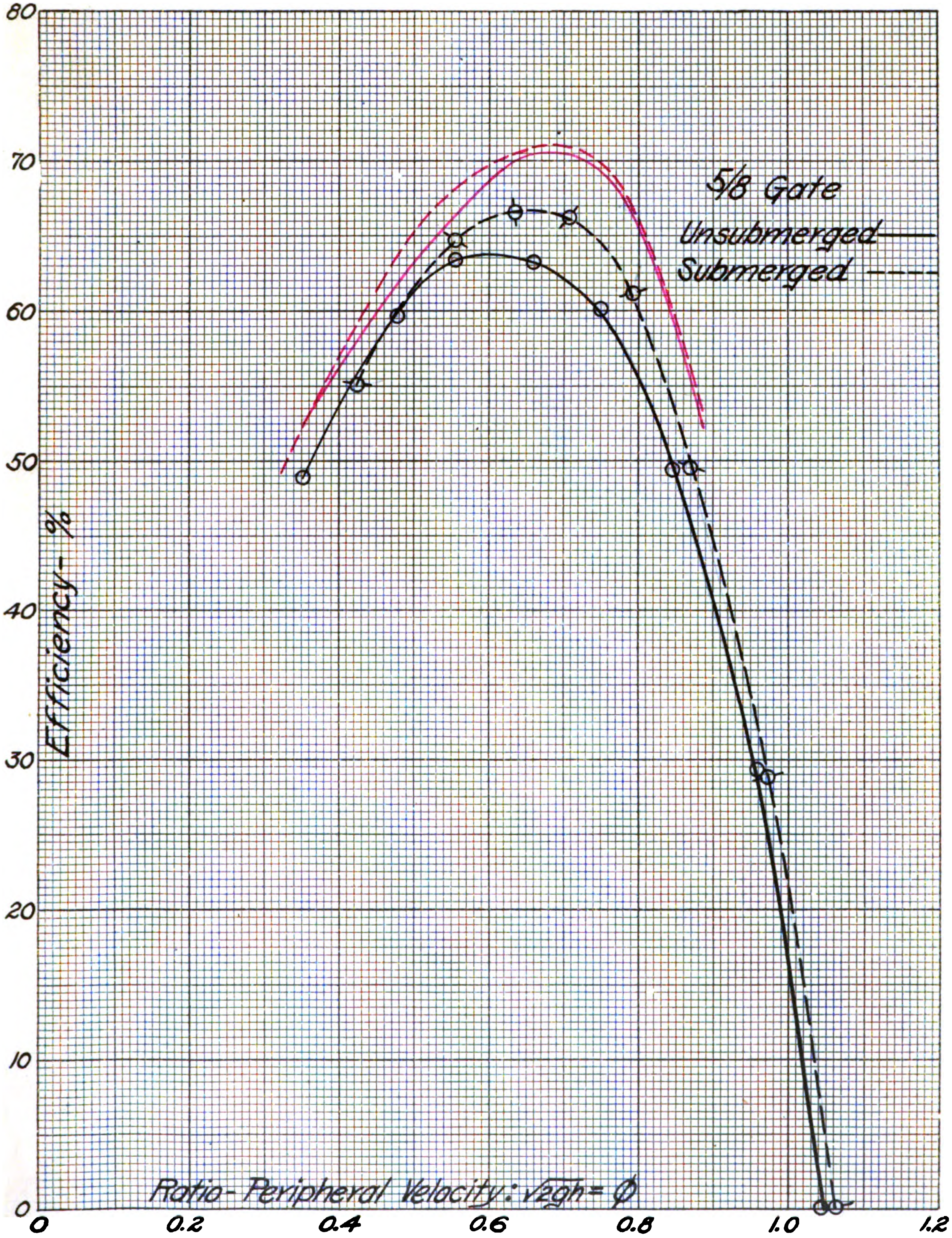
1/2 GATE - 5½ ft. HEAD


1/2 Gate
Unsubmerged
Submerged
Revolutions per Minute
Brake Load - lbs.
0
100
200
300
400
0
10
20
30
40
50
60

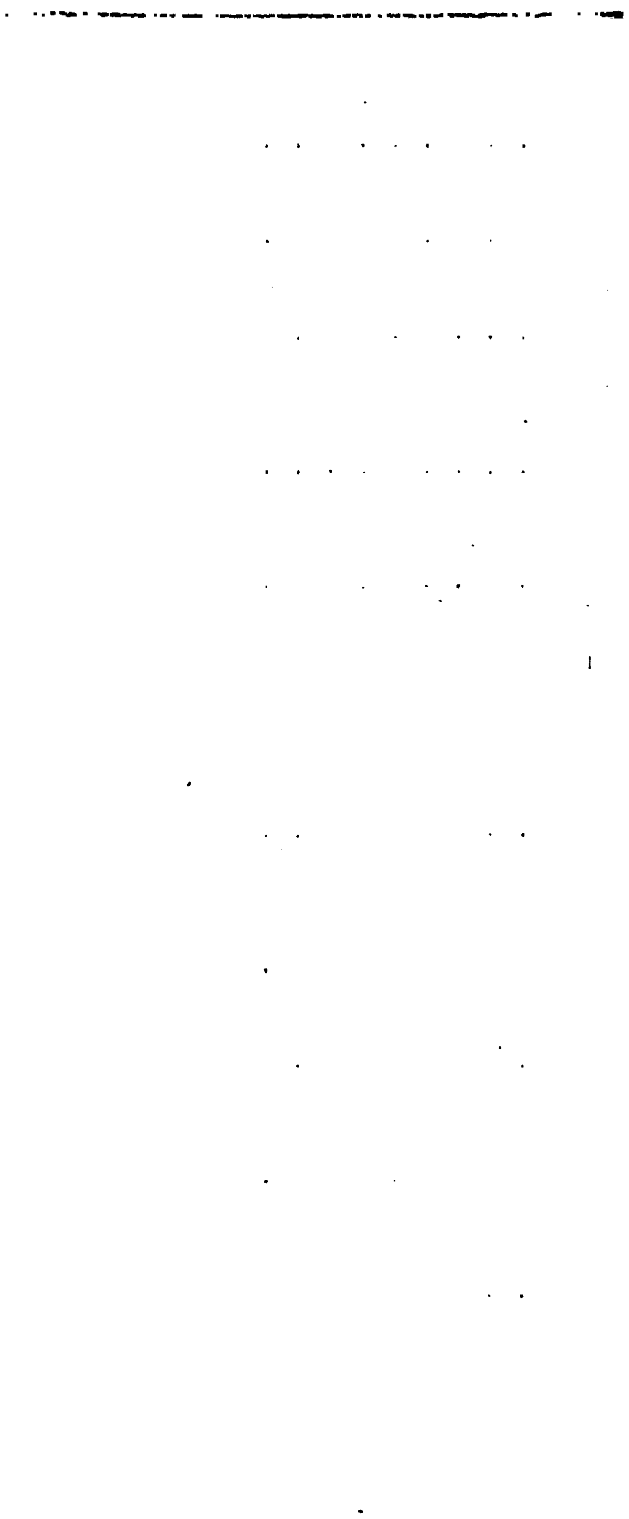

80
70
60
50
40
30
20
10
0
Efficiency - %
1/2 Gate
Unsubmerged
Submerged
Ratio- Peripheral Velocity : √2gh = Φ.
0
0.2
0.4
0.6
0.8
1.0
1.2

5/8 GATE - 5½ ft. HEAD


5/8 Gate
Unsubmerged
Submerged
Brake Load - lbs.
Revolutions per Minute
0
10
20
30
40
50
60
0
100
200
300
400

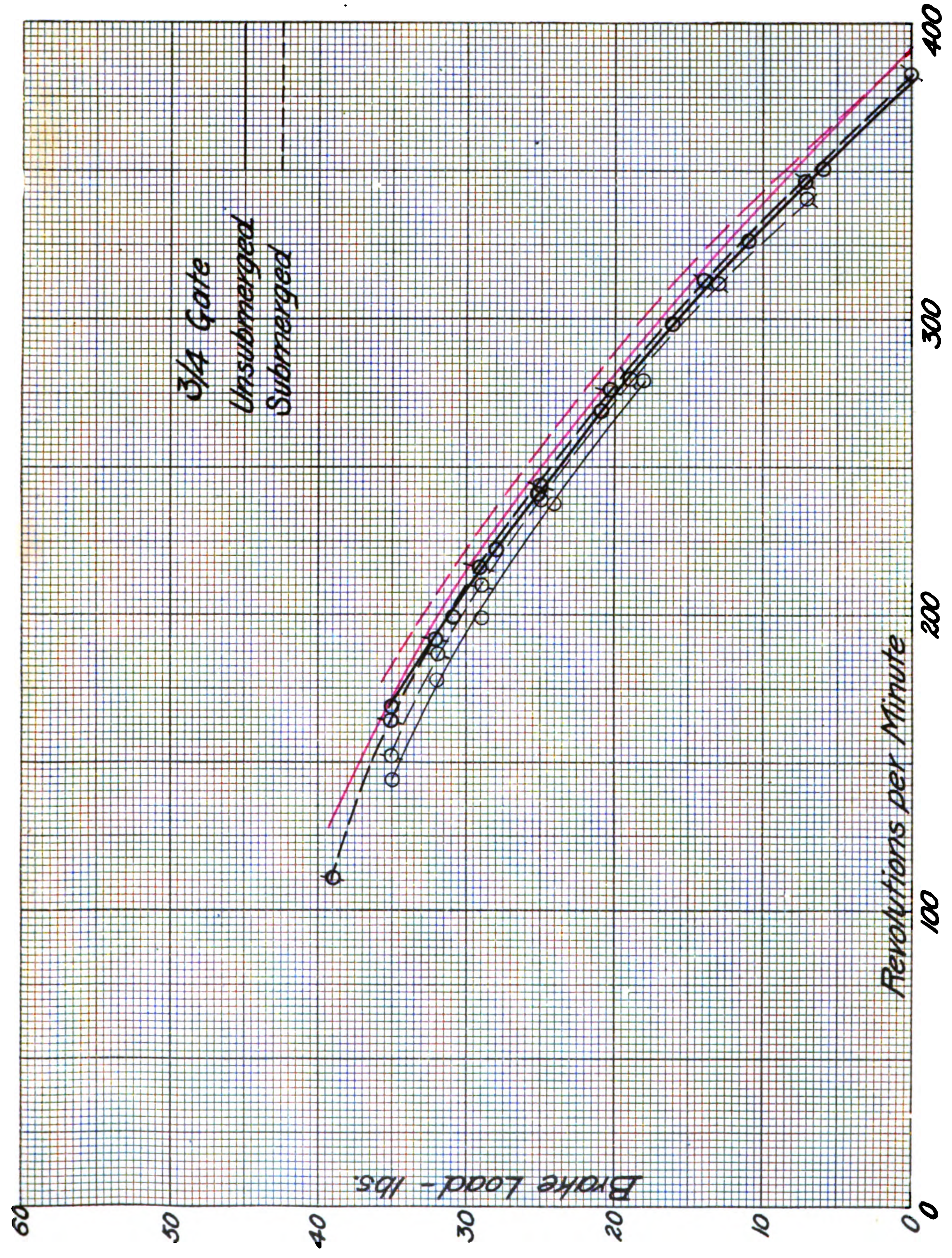

5/8 Gate
Unsubmerged
Submerged
Efficiency - %
Ratio - Peripheral Velocity : √2gh = φ
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2

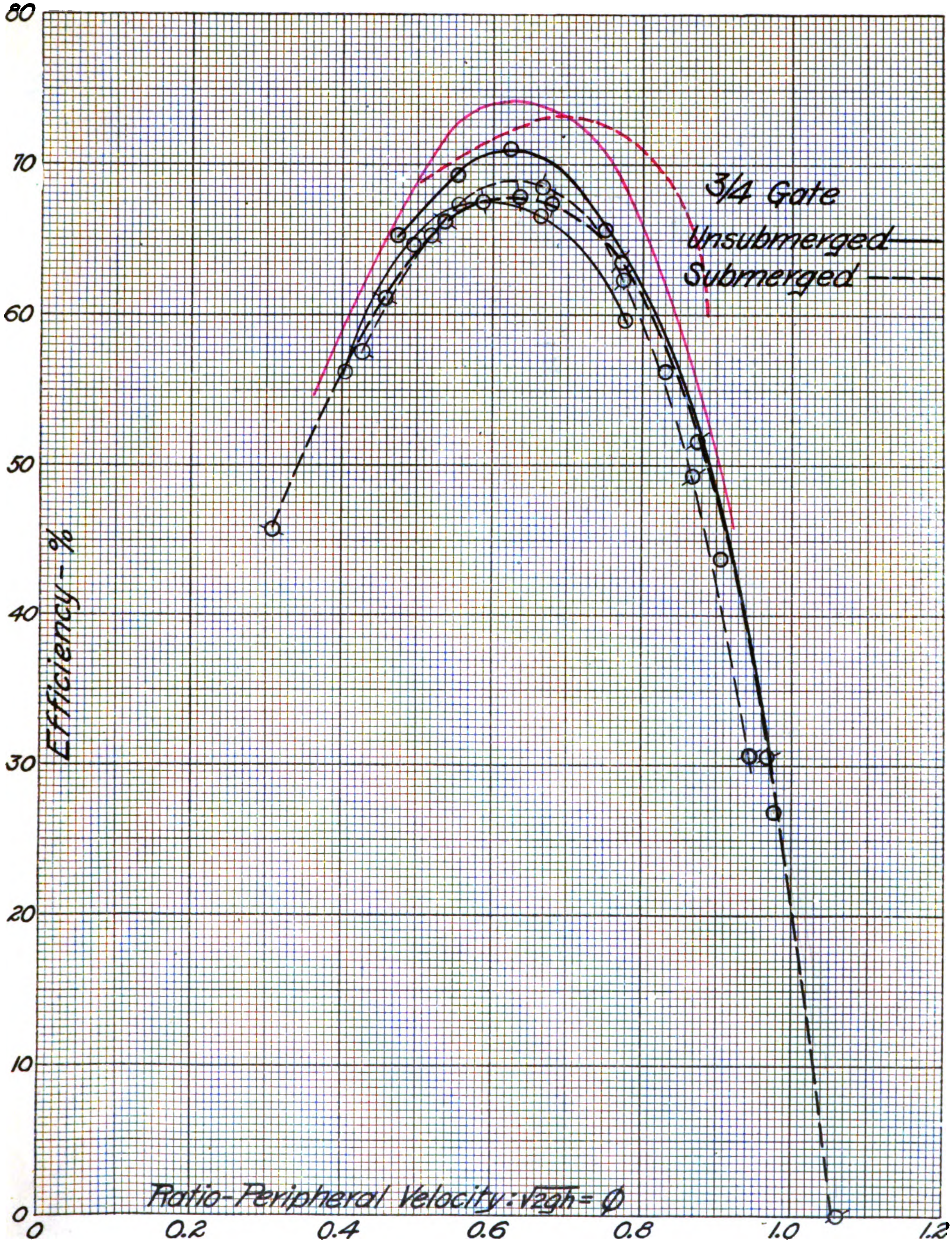
3/4 GATE - 5½ ft. Head



SECOND TEST

3/4 GATE — 51 ft. HEAD

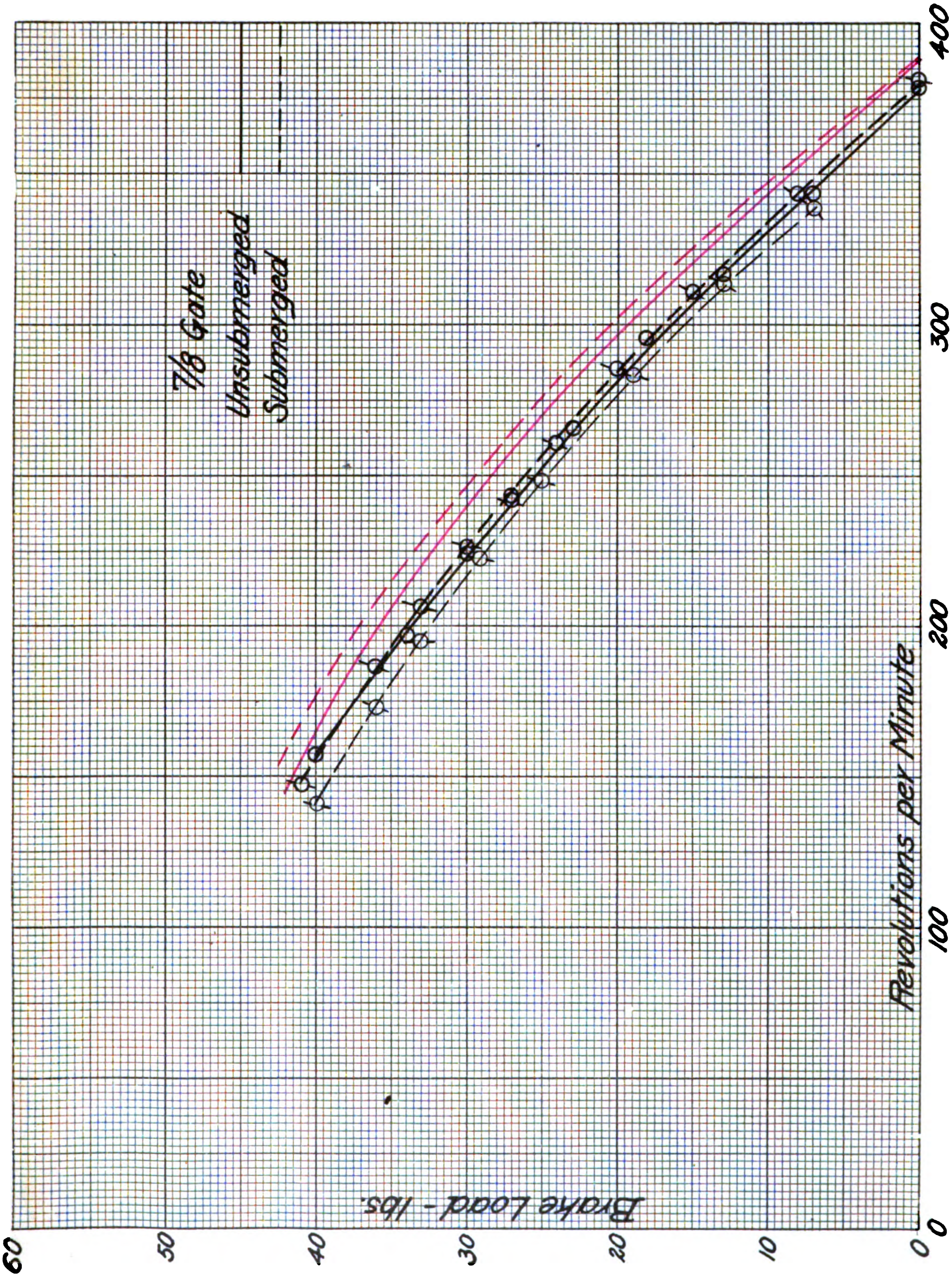

3/4 Gate
Unsubmerged
Submerged
Brake Load - lbs.
Revolutions per Minute
0
10
20
30
40
50
60
0
100
200
300
400

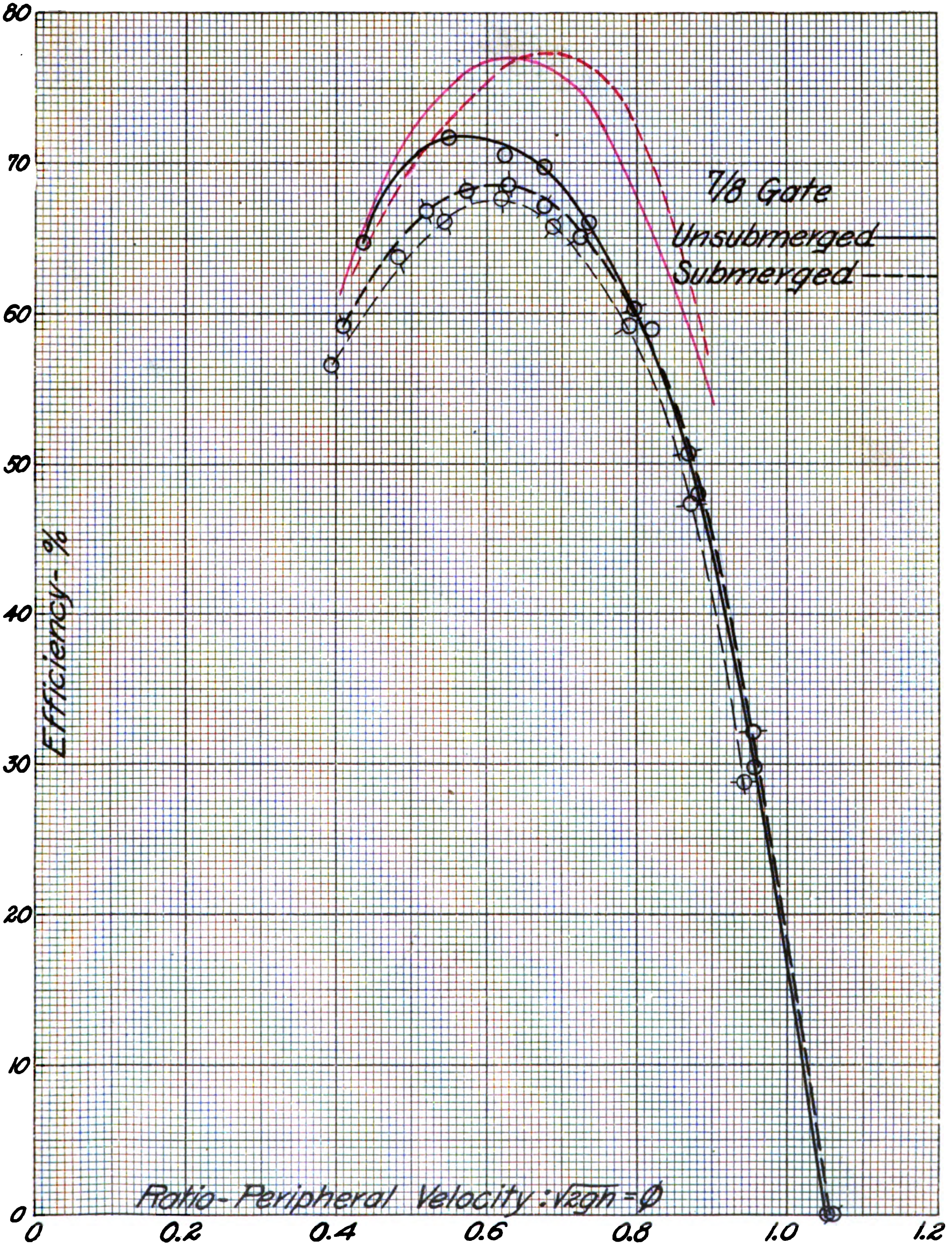

3/4 Gate
Unsubmerged
Submerged
Efficiency - %
Ratio-Peripheral Velocity : √2gh = φ
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2

7/8 Gate - 5½ ft. HEAD

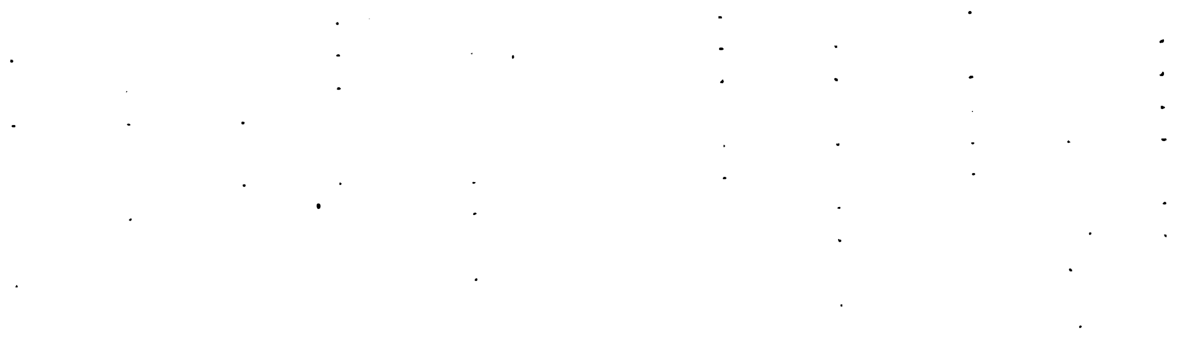
SECOND TEST

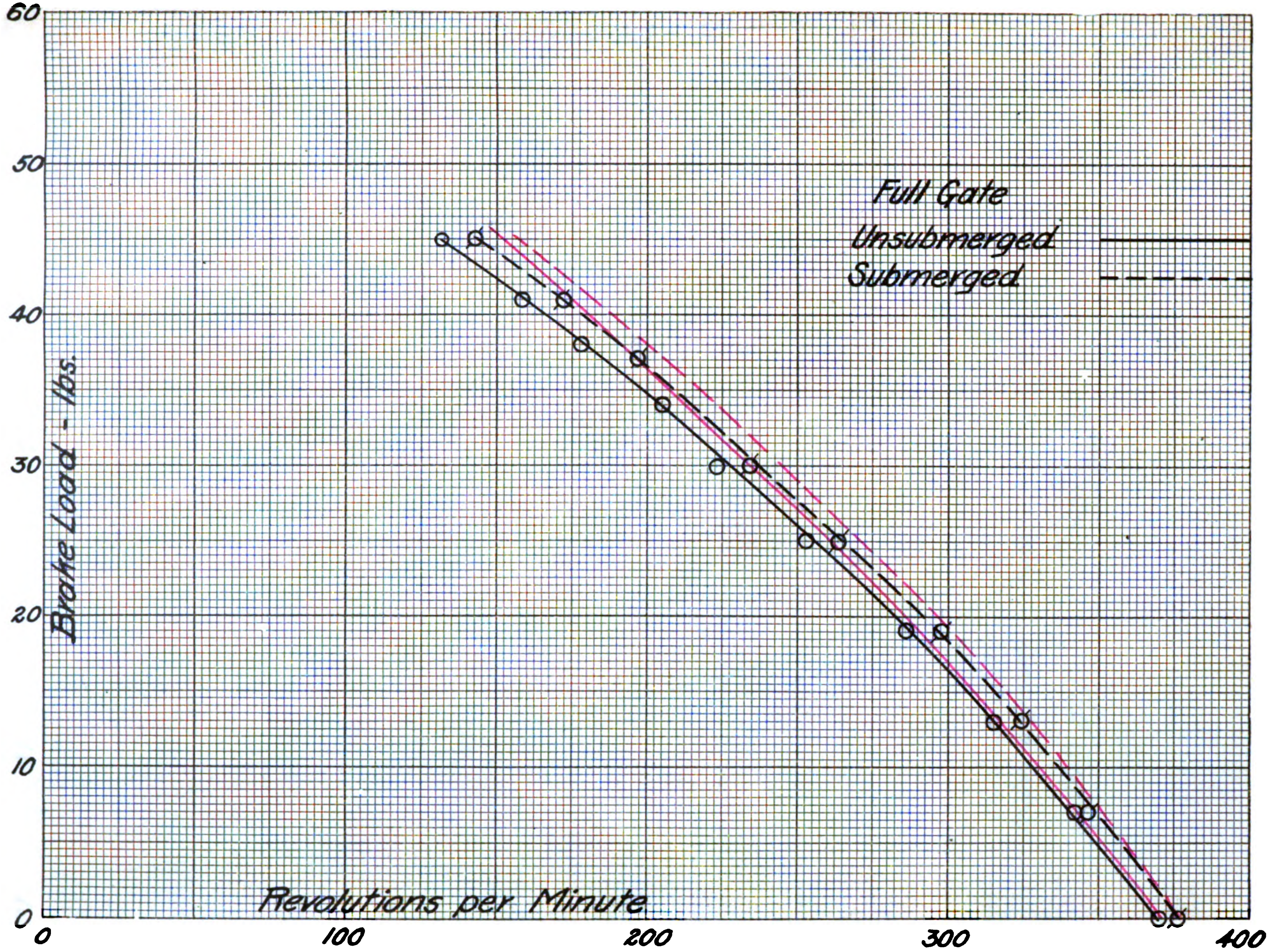
7/8 GATE - 5½ ft. HEAD

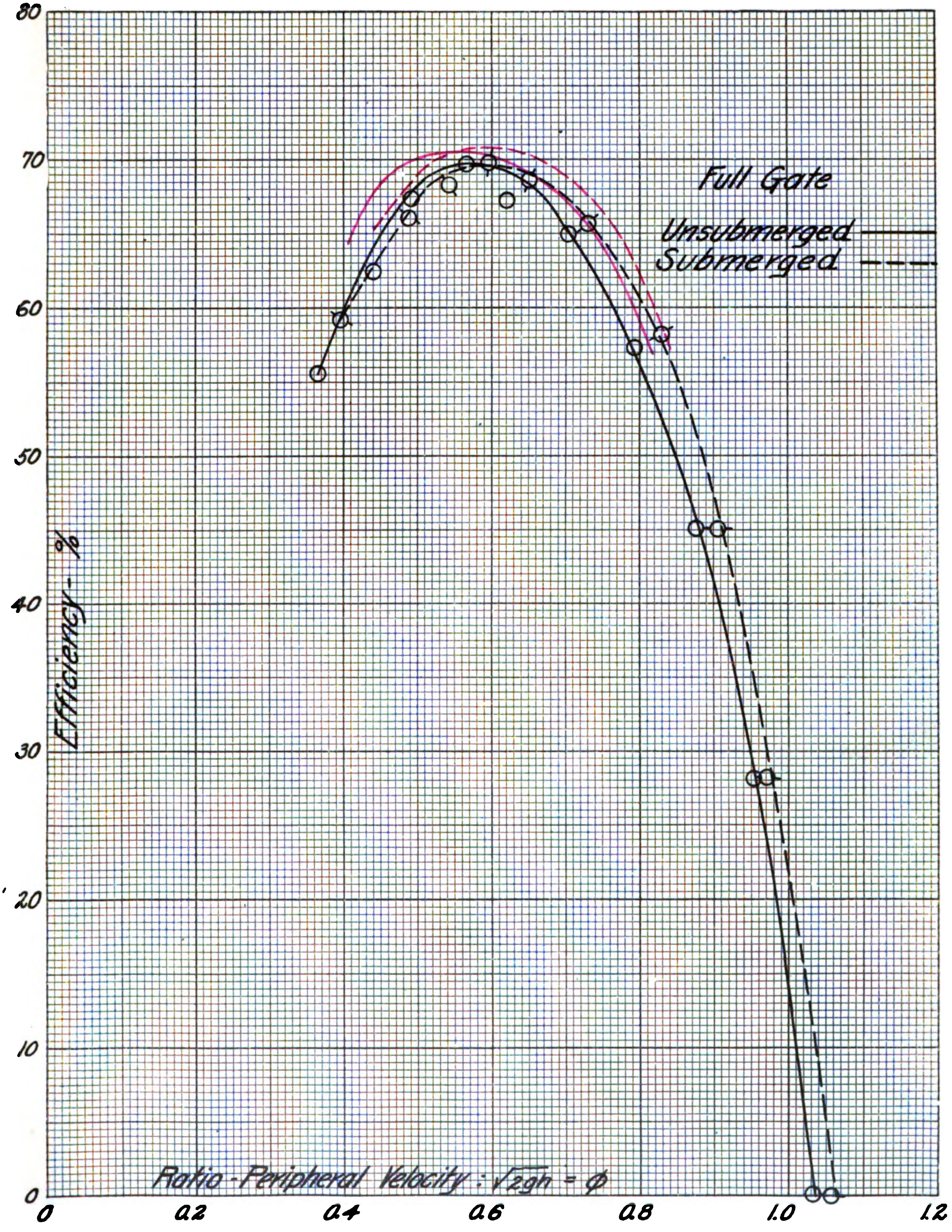

7/8 Gate
Unsubmerged
Submerged
Brake Load - lbs.
Revolutions per Minute
0
10
20
30
40
50
60
0
100
200
300
400

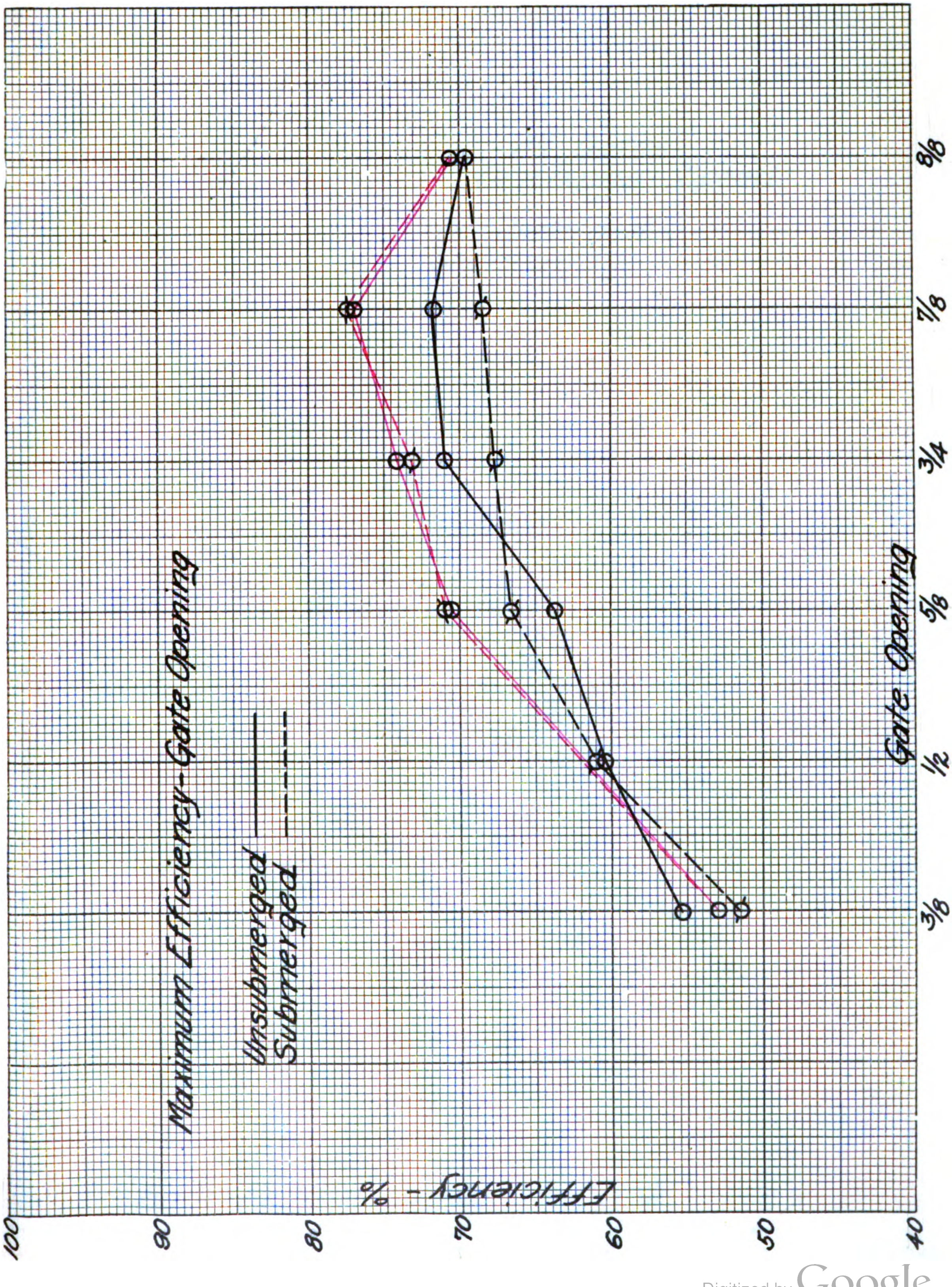

7/8 Gate
Unsubmerged
Submerged
Efficiency - %
Ratio - Peripheral Velocity : √2gh = φ
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2

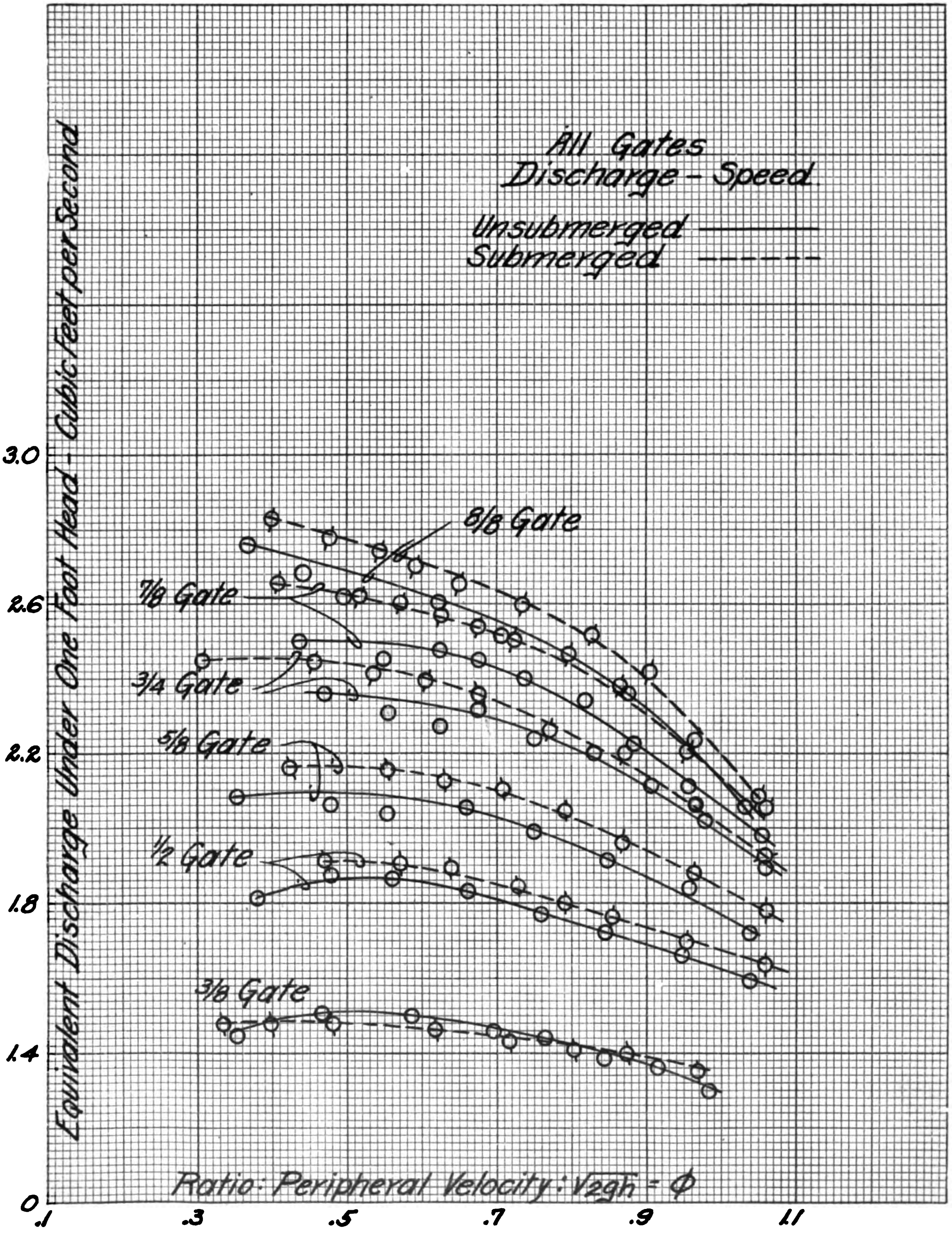
FULL GATE - 5½ ft. HEAD

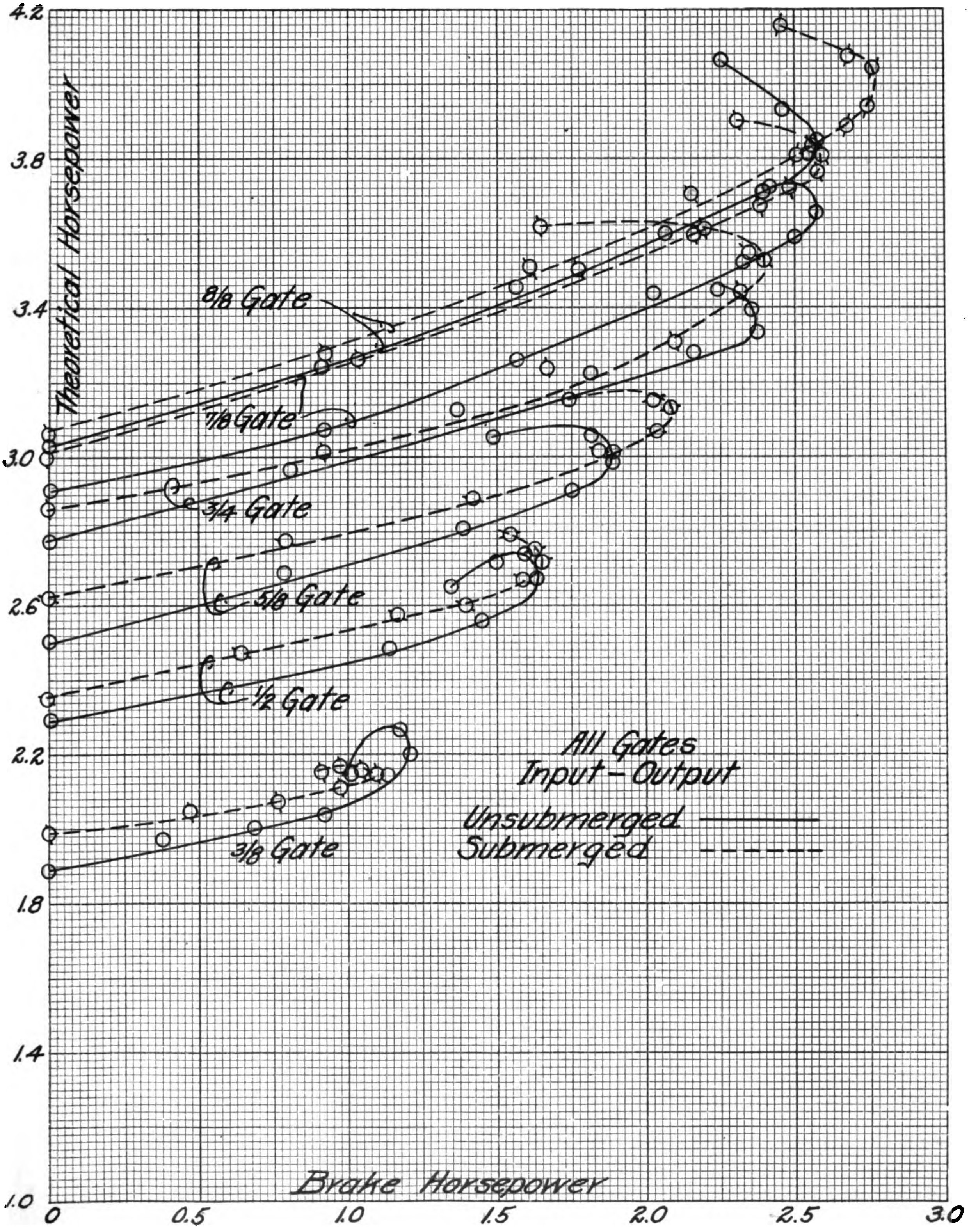



Full Gate
Unsubmerged
Submerged
Brake Load - lbs.
Revolutions per Minute
0
10
20
30
40
50
60
0
100
200
300
400


80
70
60
50
40
30
20
10
0
Efficiency - %
Full Gate
Unsubmerged
Submerged
Ratio - Peripheral Velocity : √2gh = φ
0
0.2
0.4
0.6
0.8
1.0
1.2


Maximum Efficiency-Gate Opening
Unsubmerged
Submerged
Gate Opening
3/8
1/2
5/8
3/4
7/8
8/8
Efficiency - %
100
90
80
70
60
50
40


All Gates
Discharge - Speed
Unsubmerged
Submerged
8/8 Gate
7/8 Gate
3/4 Gate
5/8 Gate
1/2 Gate
3/8 Gate
Equivalent Discharge Under One Foot Head - Cubic Feet per Second
Ratio: Peripheral Velocity : $\sqrt{2gh}$ = ϕ
3.0
2.6
2.2
1.8
1.4
0
.1
.3
.5
.7
.9
1.1


Theoretical Horsepower
Brake Horsepower
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0
0.5
1.0
1.5
2.0
2.5
3.0
8/8 Gate
7/8 Gate
3/4 Gate
5/8 Gate
1/2 Gate
3/8 Gate
All Gates
Input – Output
Unsubmerged
Submerged

DISCUSSION OF RESULTS

The experiments of Jessup and Schieber made in 1912, showed that for a given speed the unsubmerged condition carried a greater load. The experiments of Rather, Vaughn, and Noyes, made in the summer of 1912, showed the reverse of this to be the case at most of the gate openings; i.e. for a given speed the submerged condition would carry the greater load. The results of the experiments of this thesis upon the same turbine as used by Rather, Vaughn, and Noyes, check their results in this regard excepting at the low gate opening. (See pages 30, 33, 36, 40, 44, 47.). A different make and different type of turbine was used by Jessup and Schieber and no definite relation can logically be placed upon a comparison of their results.

Both of the former theses are inclined to give the impression that the efficiency of the turbine is decreased when placed in a submerged condition, although no definite conclusions to this effect are drawn. This idea was based upon a study of the efficiency - ϕ curves for all gate openings. The curves from the data of the present experiments (see pp. 31, 34, 37, 41, 45, 48), and the experience encountered in making the tests, lead the writers to strenuously object to any permanent idea of this nature based upon the results obtained. It is believed that the conditions of operation, the small head and necessarily small loads used in

conducting the tests, were such that the experimental error was greater than any effect which might exist due to submergence. This idea is borne out by the non-uniformity of results of tests run under both conditions, and by the fact that exceptions to the idea advanced are found in both of the former theses. These exceptions are found at inconsistent gate openings, such as the 5/8 gate with the higher efficiency for the unsubmerged condition for gate openings above and below.

Furthermore, it has been found by experience that the slightest foreign matter in the turbine affects the results to a remarkable extent. A little piece of waste, a leaf, a grass, or any small foreign material caught in the runner of the turbine affects the efficiency to a freater extent than the difference which the former theses would lead us to believe was due to submergence. The experiments of the present thesis were run in the winter when the surface of the lake was frozen, and the water was as clear as at any time possible. It is believed that these results are as correct as it is possible to obtain results under the conditions existing. It is not believed by the present writers that the effect if any, of submergence, is within the limits of the experimental error of the present conditions, and hence no conclusions in regard to the general purpose of this thesis

can be drawn. The Maximum Efficiency-Gate Opening curves, p.49, show the variation in efficiency.

The results of the former two theses and of this thesis are sonsistent in indicating that there is a greater discharge with the turbine submerged than with it unsubmerged for a given value of ϕ or for a given load. This is shown by the curves on p.50. The cause of this is extremely uncertain and difficult to conjecture. As the efficiencies under both conditions are practically the same it follows that for a given ϕ or for a given load the power developed is greater under the submerged condition than under the unsubmerged condition. The curves on p. 51 show the relation of input to output.

The results of the experiments of this thesis and of those performed by Rather, Vaughn, and Noyes, have been plotted together upon the same sheets. The latter results are plotted in red ink. Wide variations are seen to exist between the results of the two sets of experiments. This variation is consistent throughout, however, the efficiencies as obtained in this thesis being less in all cases than those obtained in the former thesis. This variation affects in no way the purpose of the tests, and may be accounted for by many things. The turbine was reset before running the present tests, the bearing blocks were tightened slightly, the gage in the still water ba-

sin at the weir was set at a slightly different zero. Each of these facts would have its effect upon the results, but as they remain the same throughout the entire set the actual effects are not important.

Upon the curve sheets for the 3/4 and 7/8 gates have been plotted the results of a second run made some time later than the original run. This was done in order to see how closely the work would check, and to determine to what extent experimental error might account for the variation of the results obtained. It will be noticed that the curves indicate the experimental error to be as great as $2\frac{1}{2}$ %, and as before mentioned of course throws out any conclusive ideas as to the small effect of submergence.

CONCLUSIONS

1. No definite conclusions as to the original purpose of this thesis can be drawn. (See discussion of results).

2. The discharge for a given load or speed is greater under the submerged than under the unsubmerged condition.

3. For a given load and a given speed there is more power developed under the submerged than under the unsubmerged condition.

4. The effect of submergence on the efficiency of the wheel is small. The conveniance of placing the turbine so thet it might act submerged part of the time would be the determining factor.

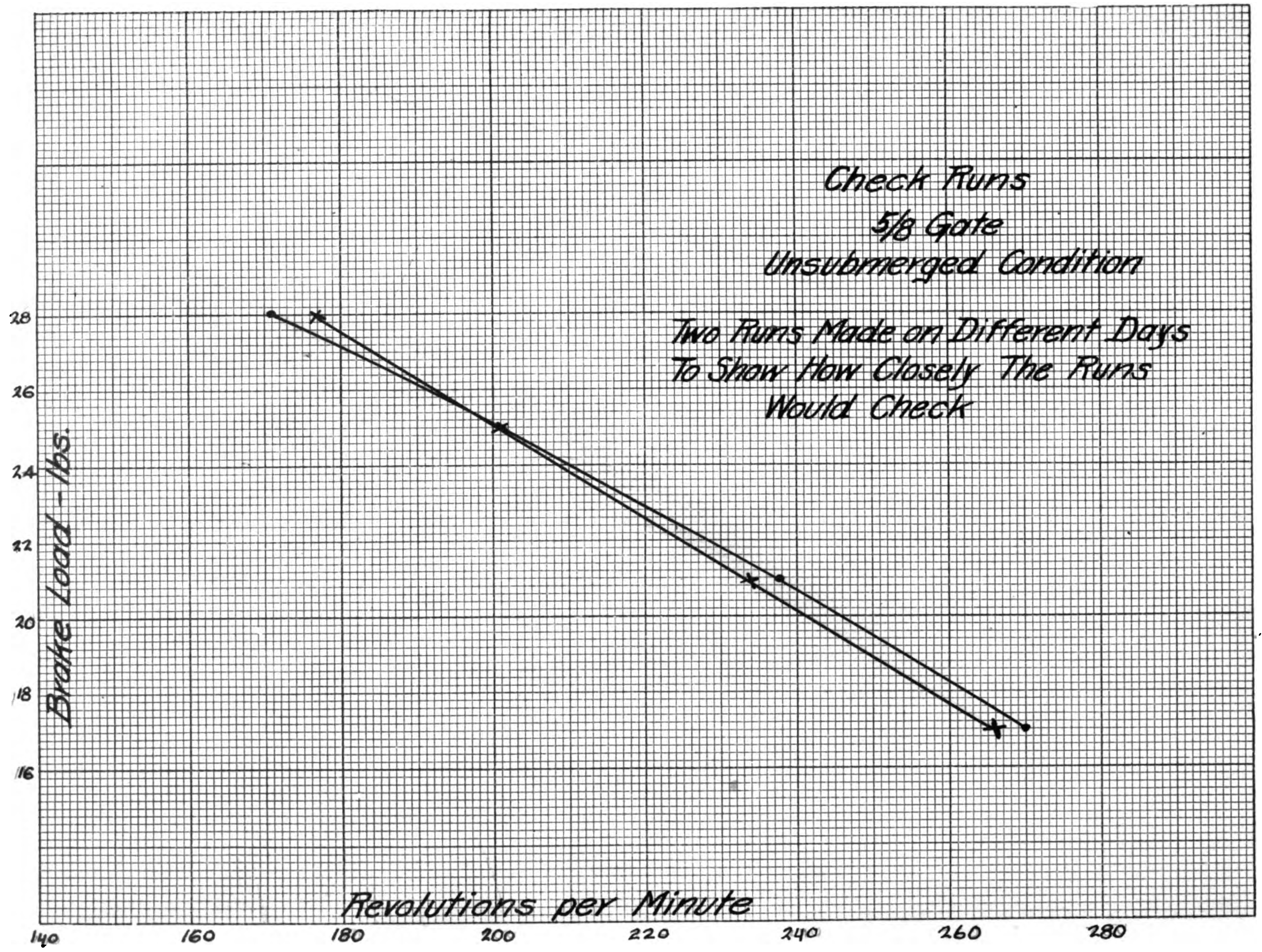
5. It is believed that further tests with the same apparatus would accomplish little. It is suggested and hoped that tests with higher heads, and loads great enough so that experimental errors would be inappreciable will be made so as to determine the interesting and important question as to just what effect submergence has upon the efficiency of a water turbine.

APPENDIX

In order to determine how much of the variation was due to experimental error, duplicate tests were made as follows. The gate was set at 5/8 opening and tests for four different loads covering the peaks of the efficiency curve were made. Conditions were left absolutely the same for 24 hours and then the same four tests were made over again. The results, tabulated and graphical, are shown on the following pages. The maximum variation in efficiency was .7 %. This is not as great a variation as the writers feel inclined to attribute to experimental error. However, it must be remembered that these two runs were made under the best conditions, and if anything would represent a minimum of experimental error. With a margin of fifty percent it may easily be assumed that the variation might be from 1.0 to 1.5 %.

It is quite evident, therefore, that with the low head and other conditions under which the turbine is tested in this particular case, it would be groundless to say that a variation in efficiency of one percent existed due to submergence of the turbine.

CHECK RUNS

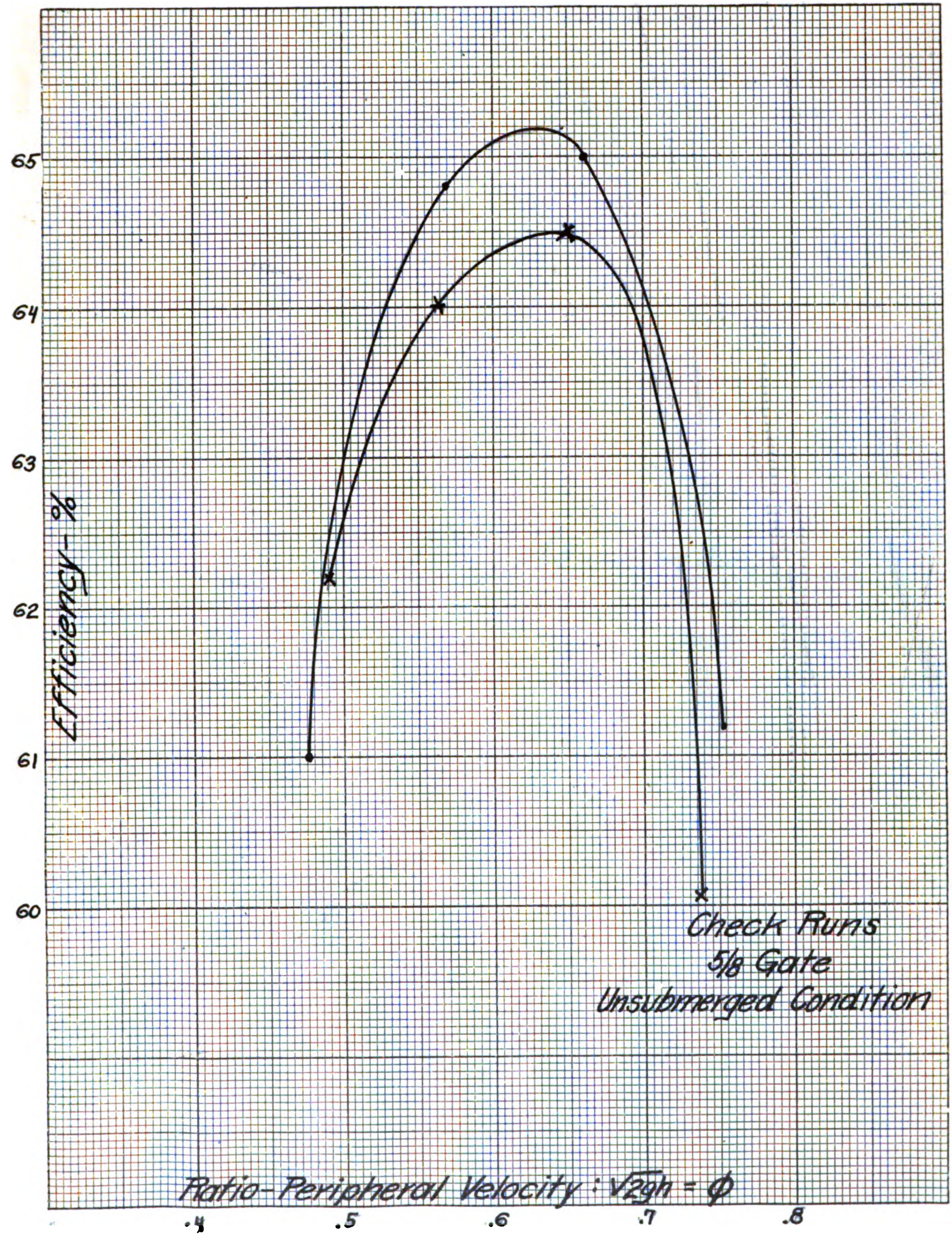


Check Runs

5/8 Gate

Unsubmerged Condition

Two Runs Made on Different Days
To Show How Closely The Runs
Would Check



Check Runs
5/8 Gate
Unsubmerged Condition

APPROVED:

C. R. Weidner

June 1, 1913.

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